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Effects of Reduced Sensory Stimulation and Assessment of Countermeasures for Sensory Stimulation Augmentation

A Report for NASA Behavioral Health and Performance Research: Sensory Stimulation Augmentation Tools for Long Duration Spaceflight

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EXECUTIVE SUMMARY

In looking forward to long-duration space missions (LDSMs) to Mars and asteroids, the Behavioral Health and Performance (BHP) Element of the NASA Human Research Program (HRP) has identified the potential development of adverse behavioral conditions and psychiatric disorders during a mission as a highly significant risk. A major contributor to this risk is the reduced sensory stimulation and sensory monotony experienced in isolated, confined, and extreme (ICE) environments. Reducing this risk requires the development of countermeasures for augmenting sensory stimulation during LDSM. This document reports the results of a literature review and operational assessment aimed at identifying key factors relevant for sensory stimulation and sensory augmentation. A review was conducted of existing literature on the effects of reduced sensory stimulation, sensory monotony and isolation, with a focus on literature from spaceflight and LDSM analogs such as Antarctic stations, nuclear submarines, and Mars mission analog studies published in the past two decades. The review explores effects on perception, cognition, affect and mood. A second review was conducted of psychology and neuroscience literature relevant for developing a theoretical understanding of the processes that link sensory stimulation levels to observed changes in perception, cognition, affect and mood (including stress). This led to the identification and dissociation of four key needs that sensory stimulation addresses, with the primary two being 1) a need for "information foraging" and 2) a need for restoration and relaxation. Potential approaches for measuring sensory stimulation and the acute and chronic effects on humans of different levels of stimulation are discussed, including self-report, behavioral, psychophysiological, and neural techniques. Frameworks for understanding personality traits relevant for sensory stimulation and for the development of personalized stimulation profiles are also presented. An initial list of potential countermeasures is reviewed, broken down by need, and the state of existing technologies relevant to these countermeasures is discussed. Separately, an interview study was conducted with seven subject-matter experts to assess the potential effects of reduced sensory stimulation during LDSM and the effectiveness, feasibility, and likely acceptance of proposed measurement methods and countermeasures. Relevant findings from these interviews are summarized. Finally, a list of specific recommendations is presented to guide future research and development of sensory stimulation augmentation countermeasures.

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SECTION 1: BACKGROUND RESEARCH ON THE EFFECTS OF SENSORY DEPRIVATION, REDUCED SENSORY STIMULATION AND MONOTONY

Framing Question: What are the effects of changes in the sensory environment that might be experienced during LDSM (deprivation/reduction in stimulation, monotony, isolation, confinement, presence of noise), and are they significant enough to warrant concern?

A wealth of research on both humans and animals has explored the effects of changes in the level and variation of sensory stimulation on behavior and physiology. In this review, we focus on work in the last two decades that has particular relevance for the challenges of long duration space missions (LDSMs). Understanding the potential effects of reduced sensory stimulation and monotony during LDSMs is an important first step for developing measures that can reliably signal an astronaut's need for sensory stimulation and for the development of effective countermeasures. Effective countermeasures for sensory stimulation augmentation will help ensure the psychological well-being of the crew and reduce the likelihood of behavioral problems that could jeopardize a mission, such as risky attempts at adventure seeking (e.g. unauthorized EVA's), behavioral withdraw, or the development of more severe mood disorders.

Isolating the potential effects of reductions in sensory stimulation is difficult. Very few situations exist in which a person is completely devoid of any sensory stimulation. On the other hand, cases of isolation (solitary confinement, sensory deprivation experiments) confound reduced sensory stimulation and social isolation, making their effects difficult to separate. Analog environments consisting of small crews (which provide a social element) that are in otherwise unchanging environments for long durations may provide the most suitable environments for isolating the potential effects of reduced sensory stimulation and potential countermeasures on perception, cognition, mood and well-being.

This section will present background research on the effects of sensory deprivation, monotony and isolation from a variety of scientific disciplines and from studies in analog environments.

1.1 SCIENTIFIC STUDIES OF SENSORY DEPRIVATION AND ENRICHMENT

1.1.1 Behavioral Effects of Sensory Deprivation and Isolation. Between 1950 and the mid-1970's, a number of research labs directly explored the effects of placing a human in an isolated and sensory deprived environment. Given the extensive reviews of these human sensory deprivation experiments elsewhere (e.g. Zubek, 1969), this literature will not be reviewed here, except to mention some of the overarching conclusions that are relevant to sensory stimulation augmentation for LDSM. These experiments confined individuals, alone, either in a bed in a small room or in a water-immersion tank. Individuals were asked to remain still, and sensory stimulation was either minimized or greatly reduced in variance. Results suggested that this "restricted environmental stimulation technique" (REST) could lead to a variety of perceptual, cognitive and emotional symptoms (including hallucinations; Suedfeld, 2010). A recent historical review of this work highlighted the long-standing claims that complete sensory deprivation can cause a person to be more susceptible to suggestion and constitutes severe mental harm (Raz, 2013). Subsequent work by Suedfeld has contradicted some of these earlier findings, leading him to claim, "neither the simulation subjects nor the astronauts whom they were simulating actually suffered serious impairments." (Suedfeld, 2010) While it is clear that complete, extended isolation can adversely affect mental health, these experiments on complete deprivation are, as Suedfeld points out, perhaps less relevant to understanding the potential negative consequences of milder forms of reduced sensory stimulation, as would occur during long-duration spaceflight with small crews.

Despite the difficulty in extrapolating the findings of these early studies to LDSM, several recent findings reported in the past two decades point to the continued theoretical usefulness of the concepts of deprivation and isolation for explaining the effects of sensory stimulation levels on human behavior. Studies that have specifically used isolation of humans for the purpose of studying the potential consequences of spaceflight will be further discussed below in the section on analog environments. Here, we will focus on forms of sensory reduction that are likely not related to the social component of isolation. When examining this literature, a useful distinction can be made between complete sensory deprivation (SD), "perceptual" deprivation (PD), in which the mean level of sensory stimulation (brightness, loudness) is within a normal range, but the stimulation is lacking in variation and structure (e.g. a bright white but otherwise empty room, visual or auditory Gaussian noise), and sensory monotony, where sensory stimulation may contain variation and structure within a relatively short timescale (e.g. an office cubicle, a changing view of a long highway, or access to foods, reading material, music) but a lack of *novel* sensations, such that over longer timescales, the sensory environment is experienced as monotonous and unchanging (see Arias & Otto, 2011, and Section 2).

1.1.1.1 Recent Findings in Human Studies of Sensory Deprivation. Although the majority of work on sensory deprivation in the past two decades has focused on research with animals rather than humans, there are a few results that build on the earlier work and should be mentioned. Following 50 minutes of sensory deprivation, Burke, Florian, Lemasters, Moore, and Raudenbush (2013) found no significant differences on measures of creative thinking, but did find higher confusion scores and higher workload demand on the NASA_TLX task. Using transcranial magnetic stimulation (TMS) to assess cortical excitability, binocular deprivation for 48 hours was found to lead to a rapid increase in cortical excitability (decrease in phosphene threshold) that returned to baseline within 2 hours of light re-exposure (Pitskel, Merabet, Ramos-Estebanez, Kauffman, & Pascual-Leone, 2007). Five days of binocular deprivation led to the opposite effect (decrease in excitability). On the other hand, 48 hours of monocular visual deprivation led to a rapid and robust decrease in visual cortical excitability (measured using paired-pulse TMS) that returned to baseline within 3 hours after the end of the deprivation (Lou et al., 2011). This suggests that the continued presence of input from one eye led to a selective suppression and silencing of neurons in visual cortex that receive input from the covered eye, whereas in the binocular condition, the complete lack of activity in visual cortex instead led to hypersensitivity. During training with a novel virtual environment, Sturz, Kilday, and Bodily (2013) found that a constrained field-of-view (FOV) of 50° led to subsequent deficits in using local and global geometric cues for reorientation, when compared to a larger 100° FOV. In the olfactory domain, Wu, Tan, Howard, Conley, and Gottfried (2012) found that while seven days of odor deprivation led to no overall changes on odor detection or discrimination, it did lead to a change in an aspect of the neural code for odors. The representation of similar odors (e.g. peppermint & spearmint) in the OFC became less similar following deprivation, and rebounded during recovery. The size of this effect was correlated with the amount of change in individual subject's ratings of odor similarity. In the tactile and movement domain, observing another person's actions while the subject's hands were tied led to an altered pattern of saccadic eye movements, suggesting that not being able to perform an action alters its observation (Ambrosini, Sinigaglia, & Costantini, 2012).

A related area of human research has investigated the behavioral and physiological consequences of deprivation-like brain states caused by partial sensory impairments, injury, or congenital deficits, such as complete blindness or deafness. Evidence for cortical plasticity in adults initially came from experiments in which some aspect of sensory stimulation was interrupted by an injury, such as digit amputation or peripheral nerve lesions. Not only can cortical representations shift dramatically following peripheral injury, but the selectivity of neural receptive fields can also shift, including their size, orientation, position and shape (Gilbert, Sigman, & Crist, 2001). These changes appear to be primarily mediated by changes in the intrinsic connectivity of cortical maps and through feedback connections from the cortex to the thalamus. It has also been reported that visual hallucinations can be experienced following vision loss, a condition known as Charles Bonnet Syndrome (CBS; Lerario, Ciammola, Poletti, Girotti, & Silani, 2013).

Studies of congenitally blind individuals has been crucial in showing that "visual" regions of the brain can be recruited by nonvisual senses (e.g. sounds, touch) during tasks that engage processes that might normally utilize those regions in sighted individuals, such as tactile object recognition or auditory spatial localization (Voss & Zatorre, 2012). Similarly, auditory brain regions of deaf individuals can be recruited by visual tasks that involve temporal sequencing. Interestingly, even a temporary blinding of sighted subjects for five days was found to enable strong crossmodal recruitment of visual areas for both auditory and tactile tasks, an effect that disappeared quickly following blindfold removal (Pascual-Leone & Hamilton, 2001).

Some forms of congenital blindness, such as those caused by cataracts, have in some cases be reversed later in life through surgery. While these individuals typically suffer from strong visual deficits such as amblyopia, visual training with video games have been found to lead to significant improvements in measures of acuity, spatial contrast sensitivity and sensitivity to global motion (Jeon, Maurer, & Lewis, 2012).

These and many other studies in humans support the notion that sensory regions in adults, even early cortical regions previously thought to be primarily static in adults, retain a significant capacity for neural plasticity. This topic will be addressed from a more theoretical perspective in Section 2 (*Low-Level Effects*). In addition, complete sensory deprivation in a sensory system does not render that part of the brain inactive, and may lead spontaneous activity and recruitment by other senses, potentially strong cross-connections amongst different parts of the brain.

1.1.1.2 Animal Literature on the Effects of Sensory Deprivation. A broad variety of perceptual, cognitive and emotional deficits have been found in animals reared in sensory deprived environments, including a reduced capacity to perceive patterns, deficits in attention, anxiety, and inappropriate responding to other animals (Barlow, 1975; Ganz, Hirsch, & Tieman, 1972; Riesen, 1975). Gluck and Harlow (1971) highlighted several theories that have been posited to underlie the effects of isolation rearing. Riesen (1966) suggested that dark rearing results in specific degeneration (atrophy) in sensory systems. Another class of theories posits that normal development of sensory systems requires postnatal stimulation, consistent with much of the literature on “environmental enrichment” (Rosenzweig, 1966; see below). A third class of theories suggests that isolation rearing leads to learning deficits, either by lowering adaptive capabilities (e.g. Hebb, 1949), through a lack of acquired reinforcement contingencies that leaves animals incapable of responding appropriately to stimuli (Harlow, Dodsworth, & Harlow, 1965; Scott, 1962), or through a failure to develop inhibitory control over responses that compete with more complex behaviors that would be demanded by changing environmental conditions (Sackett, 1970). Finally, Fuller (1967) and Sackett (1965) posit that deficits observed after isolation rearing are a form of “emergence trauma” brought on by the extreme novelty, complexity and intensity of post isolation stimulation.

This literature is perhaps of limited usefulness for understanding the effects of reduced sensory stimulation and a lack of sensory variety in healthy adults, and a review of the neural and molecular mechanisms underlying these changes is beyond the scope of this review. What is important to take away from this literature is that over the past few decades, developmental neuroscience has come to a more nuanced view of the concept of a “critical period.” Not only is there now evidence for neurogenesis in adults (Eriksson et al., 1998), but other plastic changes, such as sprouting and pruning of axons and dendrites (Engert & Bonhoeffer, 1999; Huang & Reichardt, 2001) and the growth, removal, “silencing” and “unmasking” of neural connections (Katz & Shatz, 1996; Malenka & Bear, 2004), are also now understood to continue throughout the lifespan to a greater or lesser degree in different regions of the brain. Therefore, although a normally reared individual placed in an environment with reduced sensory stimulation is not analogous to an animal reared in a sensory deprived environment, such animal models provide important clues for understanding the plastic changes in neural connectivity observed as a result of reduced sensory stimulation. For example, there is evidence that homeostatic mechanisms in neocortical circuits act to regulate firing rates of neurons (H. I. Bishop & Zito, 2013; Keck et al., 2013). These mechanisms involve a balance of excitation and inhibition, which are known to play a role in auditory synaptic plasticity (Froemke & Martins, 2011). A lack of normal sensory stimulation, such as occurs during hearing loss, can lead to an imbalance of excitation and inhibition that homeostatic mechanisms attempt to correct by reducing inhibition, potentially inducing phantom sensation (e.g. tinnitus; Yang, Weiner, Zhang, Cho, & Bao, 2011).

1.1.2 Minimal vs. Enriched Environments. Animals in captivity, though not sensory deprived in the strict sense, experience an environment that is significantly altered with respect to a natural habitat. In the worst case, an animal cage may be entirely free of smells, sights, sounds or surfaces other than the enclosure itself or those generated by the animal, it may offer no opportunities for social interaction, and may be accompanied by a monotonous diet. Although such a cage would be a far cry from even the most minimal human capsule environment, there are a number of important lessons that can be gleaned from the large literature on the effects of "minimal" versus "enriched" environments on animal health and well-being.

The concept of environmental enrichment as a method for improving animal welfare has been studied for many years (e.g. Hebb, 1947; Rosenzweig, Krech, Bennett, & Zolman, 1962). Populations living in artificial habitats have exhibited improved naturalistic behaviors and neurological functions in response to basic adjustments to their surroundings. Environmental enrichment is canonically defined as the introduction of "a combination of complex inanimate and social stimulation" (Rosenzweig, Bennett, Hebert, & Morimoto, 1978) to a habitat. Expanded interpretations require actual evidence of benefit, such as the reduction of "abnormal repetitive behaviors" (ARBs) that an animal would not exhibit under natural conditions (Mason, Clubb, Latham, & Vickery, 2007). We define it operationally as any modification to the environment that improves an animal's health, fitness, and longevity (Newberry, 1995).

Animals in captivity show signs of anxiety and stress through their behaviors and coincident physiology. General indicators include decreased socialization with cohabitants and a general decrease of activity. Species-specific adverse behaviors include over-grooming, self-biting or self-harm, and rhythmic rocking or pacing (to the extent that sores form, and often at the expense of "natural" behaviors such as courting and child-rearing). Some animals exhibit impairments in learning and memory. For example, rodents raised in standard housing perform worse than their enriched counterparts in spatial memory tasks such as water mazes and T-mazes (Van Praag, Kempermann, & Gage, 2000). It is unclear whether this is a consequence of decreased ability or motivation, though there are likely elements of both.

Anatomical, chemical, and electrophysiological measurements substantiate the depressed welfare suggested by the behaviors of animals in these environments. Van Praag et al. (2000) report increases in brain weight, DNA/RNA content, and brain proteins such as growth factors and receptors have all been found in response to enrichment. Further, they note an increased prevalence of synaptogenesis, dendritic arborization, and glio- and neuro-genesis – all associated with neural plasticity. These, in addition to distinct electrophysiological responses (e.g., stronger field potentials, improved EPSP strength, and increased LTP amplitude), are correlated with improved learning and memory (Van Praag et al., 2000).

Newberry (1995) offers several suggestions for ways to achieve improved health and wellness of captive animals, each associated with producing goal-directed behaviors that the animal finds rewarding. 1) Increase the size of the group sharing the habitat. Having more members provides greater opportunity for varied social interaction. Note, however, that there are limits: *overcrowding* a small space with too many inhabitants can have unhealthy effects. 2) Provide multiple methods of food acquisition and preparation for a variety of different foods. This provides the animals with the opportunity for choice and allows for appropriate adaptations to changing nutritional requirements. 3) Make changes to the physical environment, such as increases in the complexity or division of space into functional areas. This provides opportunities for exploration. 4) Expose the animal to an external environment. Exposure to plants, light, and complex scenery is associated with reduced stress and improved health. 5) Introduce "toys," physical stimuli with which to play and interact. These should be sufficient in number (so that multiple subjects are not competing for limited prized resources) and variety (to keep the subjects interested).

Specific sensory stimulations underlie many of these environmental enrichment methods. Research in this area has identified a range of factors across sensory modalities that are considered for enrichment of animal environments. Note that for humans, individual differences in preferences likely have a stronger impact than is suggested by the animal enrichment literature.

Below, we will summarize a number of highlights from Wells (2009) on various approaches to enrichment. One approach involves exposing animals to audio recordings of conspecifics (or their prey) in their natural environment. This has resulted in increased activity, generally understood to represent a welfare improvement. Another auditory approach exposes animals to sounds they would not likely hear in nature. A variety of behavioral and physiological readouts across many species suggest that country classical music have positive effects on animal anxiety, aggression, and growth.

Exposing animals to odors from their natural environments also affects their welfare - the scent of prey increases activity and socialization in lions, and odors from threatening stimuli (e.g., the scent of predators) tend to result in increased anxiety and aggression (in mice, sheep and cattle), though some scientists argue for improvements (vigilance in horses). Exposure to certain non-natural odors (e.g., essential oils) has improved animals' health, relaxation, and stress. Others have the stimulating effect of increasing activity and socialization. Mentioned, but not significantly addressed, is the removal of olfactory stimulation. Urine, sweat, and body waste may provide unwanted noxious stimulation.

Television and video images have also been used to study the effects of visual stimulation of captive animals, and have been shown to have positive behavioral results in many species. Although it might be expected that "biologically meaningful stimuli" should have the greatest enrichment effects, evidence suggests that the novelty of exposure to changing stimuli yields greater attention and attraction.

Often utilized as tests of cognitive abilities, computer-based games and challenges have mixed results. Some reports praise their inclusion as improving animal activity, while others have reported increases in aggression and anxiety resulting from either the complexity of learning a new task or competitiveness over available resources.

Mirrors are used for enrichment of socially isolated species. From physiological readings (heart rate, endocrine reactions) to reduced abnormal behaviors to increased activity, mirrors as enrichments seem to be generally positive. Mice and rabbits have exhibited increased "vigilance," which has been interpreted as anxious behavior. However, there is no evidence to suggest any anxiety response to mirrors extends to intelligent, predatory animals such as humans.

Certain species have preferences and aversions to particular colors in nature. Incorporation of such colors in an animal's housed environment has expected effects of enrichment. Studies have shown aversion to "warm" colors such as red in birds, mice, and primates, and preferences for "cooler" blues and greens. Such insights form the basis for "colour therapy" treatments of depression and anxiety in humans.

It is important to consider that the consequences of environmental enrichment are unlikely attributable to one single variable. For example, socialization or passive observance of stimuli will not cause significant enrichment on their own (Van Praag et al., 2000). Rather, a combination of arousal, learning, and voluntary motor behavior all seem to play a part in the enriching effects. In rodents, voluntary exercise on a running wheel is closely associated with new cell proliferation in the brain, whereas stimulating enrichment is associated with cell survival. Van Praag notes, "Essentially, all measures affected by an enriched environment depend on, and have not been dissociated from, an increase in voluntary motor behavior or exercise."

1.1.3 Noise. The need for mechanical equipment that maintains critical life-support functions while in ICE environments results in consistent, high decibel background noise.

While a large amount of this noise can be dampened, it is likely that at least some habitable portions of any LDSM transit vehicle or planetary habitat would be subject to loud background noise. Work in zebra finches, a songbird that develops a stable adult song, has shown that superimposing noise on the normal auditory feedback a bird hears when they sing leads to a gradual degradation of their stable song (Zevin, Seidenberg, & Bottjer, 2004). This suggests that auditory feedback is actively used in the adult songbird for the maintenance of stable song. A similar effect is observed in humans, where deafening during adulthood leads to the gradual degradation of speech (Cowie, Douglas-Cowie, & Kerr, 1982). The bird song system compares the auditory feedback from the bird's own vocalization to the stored memory of what the song should sound like, and the resulting error signal is used to calibrate motor system output (Roy & Mooney, 2007). In the presence of noise, the perturbation of input can lead to an incorrect error signal, resulting in an alternation of the song pattern. It is unknown whether constant background noise can have a similar effect on the human perception and production of speech.

1.2 ANALOG ENVIRONMENTS

1.2.1 Description of Analog Environments. A variety of environments have been identified as analogs for LDSM. While several of these analogs capture important aspects of long-duration spaceflight (such as isolation, confinement, the extreme nature of the external environment, long duration, a communication lag, lack of ability to quickly "abort" and return home, persistently high levels of danger, variation in workload, sensory deprivation and monotony), none of them capture all of the analogous aspects. Here, we briefly mention several classes of analog environments and highlight aspects of those environments that are most relevant for LDSM. Using the NASA Analog Assessment Tool, these environments can be classified according to the ways in which they are similar to LDSM.

1.2.1.1 Low-Earth Orbit. Short-term missions and longer-duration stays at space stations in low-Earth orbit (LEO) are excellent ways to study the effects of spaceflight on human behavior. Missions on board the International Space station (ISS), as well as previous shuttle missions and stays on the Mir, Salyut and Skylab stations provide high fidelity analogs for microgravity, the general nature of the capsule environment, and aspects of the confinement and constant danger that would be experienced during an LDSM. However, there are a number of important ways in which low-Earth orbit studies differ from LDSM. First, the habitable volume of ISS is much larger than any likely LDSM capsule scenario. Second, ISS missions typically involve 6-month stays, significantly shorter than the 20 to 30 months required for an asteroid or Mars mission. Third, while "space junk" is a real concern for ISS, as is equipment failure, the threat of a mission-endangering accident is greatly reduced compared to what would be experienced beyond LEO, and in the event of a catastrophic equipment failure or debilitating health issue, there is the possibility of return to Earth in a matter of hours. Fourth, the degree of isolation is significantly reduced in LEO - Earth is constantly visible, and astronauts have constant access to real-time communication with Earth, whereas astronauts in LDSM spaceflight will not benefit from real-time media updates or have real-time sessions with earthbound mental health staff. Finally, the workload of LEO missions is consistently high and managed by mission control, whereas LDSM missions will likely include periods of lower workload and will require that the crew be highly autonomous. For these reasons, Earth-bound analogs continue to be vitally important analogs for studying potential effects of reduced sensory stimulation during LDSM and developing countermeasures.

1.2.1.2 Antarctic and Arctic Stations. Despite improvements in access to real-time communication and media and increasing comfort of stations, long-duration scientific missions to polar research stations continue to be one of the better analogs for the social isolation and harshness of the external environment that is characteristic of LDSM. An additional aspect that makes polar research stations an excellent analog is that there is a scientific mission that makes presence in the ICE necessary, with meaningful scientific work to be done. Until recently, polar research stations were also a good analog for the "lack of return" aspect of LDSM, but that has changed in recent years as the ability to airlift individuals to safety, even during the harsh winter months, has improved.

Although polar expeditions, which involve difficult treks to remote areas, present useful opportunities to study the effects of difficult work in a harsh and isolated environment, this review will primarily focus on the "winter-over" stays, during which a team of scientists and other professional staff will stay at an Antarctic station with almost no direct external contact for a period of six to twelve months. Despite the greater access to media (compared to previous decades), this scenario still present a decent analog for studying the potential effects of reduced sensory stimulation and monotony due to the difficulty of getting in supplies for long stretches. On the other hand, winter-over stays typically involve a much larger crew and habitable volume than would be experienced during LDSM.

1.2.1.3 Navy Nuclear Submarine Missions. Maintaining a strategic advantage in global military readiness necessitates that the location of military submarines be highly protected. Submarines that utilize nuclear power sources typically do not require refueling at all during their entire lifespan, allowing them to stay submerged for extremely long periods, limited only by their food and air supply. Current submarines in operation remain submerged for 70-90 days.

Given these mission durations, Navy submarines represent an excellent analog environment for critical aspects of LDSM, including isolation, habitable volume, lack of immediate return, a dangerous external environment, and the presence of mission critical workload. In many cases, there is also lack of easy communication with the outside world, though this varies on the secrecy of the mission.

Navy submarines are also a decent analog for sensory deprivation & monotony. Only occasionally does the undersea environment provide opportunities for interesting viewing, such as when sailors are given a chance to take turns looking at the view from the periscope.

1.2.1.4 Involuntary Solitary Confinement. Involuntary solitary confinement captures important aspects of sensory deprivation, monotony and social isolation. Yet the involuntary nature of the confinement, as well as the punitive aspects of the physical environment, add a number of psychological stressors that are not present during LDSM. Unlike astronauts, prisoners are incarcerated against their will, with no purpose, very high risks to physical health, an oftentimes, no knowledge of when the confinement will end.

1.2.1.5 Hospital Environments. Hospital environments can be seen as analogs for specific aspects of LDSM, including some aspects of confinement (e.g. after recovery from serious injury when mobility is limited), sensory monotony and oftentimes, social isolation. In particular, studies on the effects of the physical environment (presence of natural elements or windows, lighting, noise, clutter, personal space) on mental health, stress reduction and recovery from injury/surgery may provide insight into aspects of capsule design for LDSM. We will not address this here, as the most relevant literature focuses on the potential benefits of natural elements for health and stress reduction, which will be reviewed in Section 2.

1.2.1.6 Earth-Analog Experiments. Given the recognition that LDSM poses specific operational and health challenges beyond previous short-term and LEO space missions, a number of specific analog testing facilities have been designed by various space agencies. The range of such Earth-based capsule environments is considerable, as they have been designed for purposes ranging from equipment testing and operator training to, in some cases, experimental tests of long-term habitability and health. Some of these facilities are located amidst large urban areas, and “isolation” is self-enforced, whereas others are located in environments that have an element of natural isolation, such as in a polar environment or undersea. One benefit of such special-purpose analogs is that they can be constructed to mimic specific aspects of LDSM capsule environments, and are thus excellent tools for looking at human factors issues and equipment testing. However, the simulated nature of such missions may make them less relevant for understanding the psychological pressures of a real long-duration space mission.

1.2.1.7 Biosphere 2. Although the Biosphere 2 experiment was a decent analog for aspects of long-term social isolation, the very salient differences in habitable volume and the nature of the capsule environment (namely, the presence of a large greenhouse) make it less relevant for LDSM. Given the excellent reviews of Biosphere 2 that exist elsewhere, this report will not include information from this study. It is of note, however, that there may be specific lessons from the Biosphere 2 study about the potential effectiveness of plants/nature as a countermeasure in isolated environments. Biosphere 2 may also be a more relevant analog for future ground-based environments, as could be envisioned on the moon or the Martian surface.

1.2.1.8 Other Analogs. Finally, a number of other analogs were considered for this report but will not be addressed in the interest of space and given the lack of more recent research on these topics. These include spelunking, cabin fever, whaling, Atlantic shipping, deep diving, and weather stations.

Potential future analogs for LDSM missions could include isolated sections of ISS and a moon-based analog.

1.2.2 Effects of Reduced or Altered Sensory Stimulation Documented in Analog Environments. In order to effectively evaluate potential countermeasures for the reduced sensory environment that an astronaut is likely to encounter during an LDSM, it is important to understand the nature of the potential effects of reduced sensory stimulation on human health, performance and well-being. Despite the fact that no one analog may capture all aspects of LDSM, experiments and surveys from analog environments are the primary sources of information on what can be expected in future LDSM missions. Below, we review research from analog environments collected over the past two decades that is relevant for understanding the effects of long-term isolation, reduced sensory stimulation, and sensory monotony on perception, cognition and affect.

A consistent issue with this literature is the difficulty of disentangling the source of an observed deviation from “normal” behavior. Although previous authors have provided useful frameworks for categorizing the stresses of spaceflight, the link between any one stressor and an observed effect is not always clear. For example, Kanas and Manzey (2008) divide stressors into four categories: physical, habitability, psychological, and interpersonal. Yet while reduced/altered sensory stimulation may be seen as primarily a psychological stressor (isolation, confinement, monotony), it is also a habitability stressor (ambient noise, changes in lighting, size and layout of one’s living space), it interacts heavily with interpersonal stressors, and is impacted by physical stressors. Three issues of this nature are repeatedly encountered in the LDSM analog literature, and will be particularly important to address for effective countermeasure development: whether an observed effect is a result of reduced sensory stimulation or another stressor, such as social isolation; what effects are due to physical aspects of being in *space*, versus habitability or psychological aspects of being in a *capsule*; whether the effects are due to *short-term adaptation* processes or are instead the result of *long-term* processes that may get worse over the duration of the mission. Where possible, we have highlighted information that may help disambiguate these factors.

An additional issue is the difficulty in disentangling experimental effects of the environment from subject population effects, such as increased "resilience" of test populations to altered sensory environments introduced by crew selection procedures. Where possible, information pertaining to such individual differences in susceptibility will be highlighted throughout the review, as well as in a specific section on individual differences.

1.2.2.1 Effects on Perception. Very few consistent changes in perception have been reported in LDSM analog environments. Although there exist anecdotal reports of perceptual changes ranging from mild changes in sensitivity to sound and light levels to object and scene hallucinations, experimental evidence for perceptual effects is rare, and a clear link to altered or reduced perceptual input (deprivation/monotony) even rarer. The most well supported perceptual changes occur due to disruptions of vestibular and proprioceptive systems as a result of microgravity. Although such changes are technically a result of changes in "sensory" stimulation of vestibular and proprioceptive systems, they will be reviewed only briefly, as such effects are not the primary focus of this review.

In fact, some authors have claimed that early reports of perceptual effects resulting from sensory deprivation were contaminated by artifacts, and that none of the subjects in those experiments showed any serious impairments (Suedfeld, 2010). Stuster (1996) even went so far as to say that sensory deprivation is not likely to be a problem during LDSM, as crews will be composed of 4 to 6 people, and research summarized by Zubek (1969) indicates that the addition of just 1 more person in deprivation experiments was sufficient to mitigate most of the perceptual effects of sensory deprivation and isolation.

Visual Effects. Several recent analog studies have specifically investigated effects on visual perception. Studies of astronauts and cosmonauts in the shuttle/Mir program report that upon encountering a microgravity environment, conflicting vestibular and visual cues lead to disturbances in the vestibulo-ocular reflex, which can have direct effects on eye movements, gaze and spatial orientation (Kanas & Manzey, 2008). Lacking gravity as a frame of reference for spatial orientation, astronauts become more reliant on visual cues to maintain a map of their surroundings and a sense of body position relative to their environment. Even with eyes open, astronauts report experiencing erroneous perceptions of self-motion, distortions in perception of body orientation (feeling like one is "upside-down") and induced perception of object displacement when moving one's head. However, these effects are short lived, typically disappearing within a few hours of entry into microgravity (though occasionally lasting longer or reappearing; Kanas & Manzey, 2008). Similarly, astronauts report a dominance of an egocentric reference frame when describing spatial relationships that lasts during an initial several-week adaptation period, and decreased effects of common geometric illusions that rely on pictorial depth cues (e.g.

Müller-Lyer illusion; Kanas & Manzey, 2008). Interestingly, mental rotation does not seem to be affected (even after 7 months in space), and face-inversion effects are still found for stimuli learned in microgravity (Kanas & Manzey, 2008). However, caution should be observed regarding the findings of face-inversion effects – a more relevant experiment would be to test for the size of face-inversion effects *after* an extended time in space, during which astronauts would be exposed to faces at many more orientations than are experienced on Earth. Yet for the most part, such deficits in visuospatial skills appear to be relatively short lived, and largely disappear after initial adaptation to microgravity (6 day MIR visit; see Eddy, Schiflett, Schlegel, & Shehab, 1998).

The Russian Space Program has reported increased sensitivity to visual and auditory stimulation that developed after 1-2 months of flight, part of a syndrome they describe as "asthenia" (Kanas et al., 2001). However, evidence for such effects is generally lacking. A 2011 paper published in Russian, based on the MARS-105 study, examined threshold frequency characteristics of the isolated volunteers (Bogatova et al., 2011). While only the abstract is available in English, it appears as if the article emphasizes the need to measure individual threshold profiles and match lighting conditions to them.

One area of concern that has received some study is the possibility that long-term confinement in a capsule environment with restricted/absent views of long distances (maximum depth of field of less than 5mm) may lead to a reduction in sensitivity to depth cues. Seeing depth relies on both monocular and binocular cues; while monocular cues (size, occlusion, parallax) are less likely to be affected by confinement, binocular cues (stereopsis, convergence) would be deprived of input in a capsule environment, and may suffer as a result (as would accommodation). Participants in the Mars-500 experiment (520 days in a sealed facility) completed 5 different tasks assessing depth perception: a 2-D relative length judgment, a 3-D relative size adjustment, a change detection task comparing saliency of changes to "near" vs. "far" pictorial features, a bisection task performed on an image with pictorial depth to measure visual space compression, and an open-field experiment in which a marker was placed in depth to match a length in the frontal plane ("post-flight" only). Performance was generally excellent, and no changes were observed over time (baseline, eight "in-flight" sessions and one post-confinement session; Sikl & Simecek, 2014). A small potential trend toward a decline in the longer distances of the open field test, but the lack of a pre-flight baseline made it difficult to interpret. The authors note that although the participants' view was restricted to a focal length of no more than 5m in most of the habitat, there was a narrow transfer tunnel that afforded a longer view and suggest that repeated performance of tasks may have led to alternate solutions. The authors also point out that no significant effects have been observed in depth perception, size constancy, form discrimination, or visual acuity in participants in sensory deprivation experiments, though these experiments typically do not exceed one or two weeks.

These results stand in contrast to reports of Navy sailors who develop esotropic strabismus (crossed eyes) as a result of having spent large amounts of time aboard submarines (Stuster, 1996). Although Sikl and Simecek (2014) did not find effects of confinement on their depth measures, it remains possible that other measures would have found effects – in particular, the distinction between "vision for identification" and "vision for action" (e.g. Goodale & Milner, 1992) may also apply to aspects of mid-range depth of field. Judging pictorial depth cues, and even judging distance in a real-world environment, may not adequately tax depth systems that would be used in interacting with medium range depths, similar to what is observed in the dissociation between susceptibility to size illusions and formation of the hand for reaching (Haffenden, Schiff, & Goodale, 2001). A driving task, or perhaps something similar to a hurdle-jumping task, could be considered as ways of testing whether confinement in small environments leads to a reduction in the ability to use medium-range depth cues for guiding motor plans.

Other than transient the spatial disorientation described above, there is virtually no evidence for changes in other aspects of higher-level visual identification such as object recognition and scene perception.

Hallucinations and Delusions. Anecdotal reports from a number of sources raise the concern that prolonged reductions in sensory stimulation may lead to hallucinations or delusions (Atlis, Leon, Sandal, & Infante, 2004; Raz, 2013; Zubek, 1969). On the other hand, Stuster (1996) suggests that although hallucinations and delusions are observed during sensory deprivation experiments, the addition of just one more person drastically reduces their incidence. In his review of polar expeditions, he found that cases of severe psychosis or neurosis were very rare, and even out of those reported, most did not seem to focus on sensory hallucinations (Stuster, 1996). Similarly, Kanas and Manzey (2008) review a number of studies that highlight the very low incidence of psychiatric problems (1-5%), even amongst Antarctic winter-over and submarine crews that undergo less stringent selection procedures than astronauts, with the vast majority of these episodes being related to mood, anxiety or interpersonal conflicts, not hallucinations or delusions. One related phenomenon is that of "sensed presence," in which members of polar treks have reported a feeling of a presence of a deceased loved-one or mentor (e.g. Atlis et al., 2004).

Altered Photoperiod. The effects of an altered photoperiod and potential countermeasures are a major area of study in space science. A large body of research has shown that human circadian rhythms, such as the sleep cycle and other important biological functions, have natural cycle lengths that are typically entrained to a 24-hour day by the presence of bright light, and are altered during spaceflight (see Barger et al., 2014; Rahman et al., 2014). Decreased exposure to bright light, as occurs during the winter months on polar expeditions, is associated with changes in mood known as seasonal affective disorder (Palinkas & Suedfeld, 2008). In the Mars-520 simulation, light exposure was found to decrease over time as a result of less wakefulness, and the majority of crewmembers showed some type of sleep disturbance (Basner et al., 2013). The use of focused periods of short wavelength (blue) light and melatonin regulation is being actively explored as countermeasures in capsule environments where access to natural light cycles is not available (e.g. Barger et al., 2012; Brainard et al., 2013).

Auditory Noise. Individuals living in capsule environments often experience constant, monotonous noise and vibration from critical life support systems (Suedfeld & Steel, 2000). In addition to the communication difficulties and stress created by constant, inescapable noise, Suedfeld points out that crewmembers in capsule environments report experiencing chronic tension as they unconsciously listen for mechanical failures indicated by the change in ambient sounds. In addition, the noise of living in a capsule in space - the “bangs and pops” of crewmembers moving in the confined quarters, noise from equipment, automatic thrusters, and the expansion and contraction of the hull from changes in temperature – can pose challenges for restful sleep (Stuster, 1996), which in turn, can lead to fatigue, decreased vigilance and poor coping with stressful events.

Proprioceptive and Tactile Changes. Motor and proprioceptive systems, which operate in tight conjunction with each other, must to adapt to changes in body mass, muscle tone, and agility over the lifespan. It is therefore likely that proprioceptive systems maintain greater plasticity into adulthood. There is evidence that the adaptation period to a microgravity environment includes alterations in proprioception from joints, muscles & skin, leading to various forms sensory-motor discordance, such as impairments in awareness of limb position and incorrect reaching trajectories that can persist beyond the initial adaptation period (Kanas & Manzey, 2008). Eddy et al. (1998) found evidence for impairments in mass discrimination during a 17-day shuttle mission, possibly due to disturbances of motor control, and there is also evidence of some slowing in speed of voluntary arm movements and effects of microgravity on manual control movements.

These issues extend to coordination of the vestibulo-ocular reflex (VOR), which results in a phenomenon referred to as “space motion sickness” (Suedfeld & Steel, 2000). In particular, the discrepancy between visual cues and vestibular/body cues of vertical are mismatched due to the lack of gravitational pull. However, it appears that for most individuals, space motion sickness lessens after the first two to four days in microgravity.

No reports were found of changes in tactile sensitivity or discrimination.

Gustatory: Food Effects. The design of food systems for spaceflight is a large and specialized topic that is beyond the scope of this review. Here we mention just a few relevant issues found in our search. On polar expeditions, increase appetite and weight gain is common, as are gastrointestinal complaints (Palinkas & Suedfeld, 2008). In the Devon Island Mars Analog (FMARS), “high effort” meals were very appreciated and rated the highest in terms of satisfaction (Binsted, Kobrick, Griofa, Bishop, & Lapierre, 2010). Fresh vegetables (lettuce and sprouts) were highly valued, as were fat sources (lard or duck fat; Binsted et al., 2010). In a review of food systems in spaceflight, Häuplik-Meusburger (2011) reported a variety of responses to existing food systems, ranging from opinions that eating was purely a necessity (e.g. Peggy Whitson onboard ISS) to quite positive reviews of food (e.g. Valentin Lebedev onboard Salyut 7, Paul Weitz onboard Skylab 2) and everything in between (e.g. good but bland, Harrison Schmitt on Apollo 17). Interestingly, the presence of greenhouses for growing a variety of foods and herbs was seen as absolutely essential by a number of astronauts and cosmonauts, both for their value as fresh food items but also for their psychological benefit (Häuplik-Meusburger, 2011). Meal times were also reported to serve a strong social function.

Smell. There is very little work documenting effects of spaceflight or long-term isolation and confinement on the sense of smell. Although it is documented that long-duration space capsules can become highly unsanitary and harbor strong unpleasant odors (Suedfeld & Steel, 2000), it is unclear whether this presents an issue for astronauts' odor discriminability or psychological well being beyond an initial period prior to adaptation. During LDSM, the more pertinent issue may be that the continuous movement of air necessitated by air filtration systems reduces the potential enjoyment of food contributed by odor.

1.2.2.2 Effects on Cognition. In contrast to work on perceptual effects, there exists a relatively robust literature on the effects of ICE environments on cognitive processes. It is well understood by NASA and other space agencies that adverse stress in a space environment can lead to deterioration of work performance and cognitive skills, and that no astronaut is entirely invulnerable to stress (Suedfeld, 2005). However, given the existing evidence, it is difficult to a) distinguish the effects of isolation and reduced sensory stimulation on "thinking" and decision-making apart from their more general effects on arousal, consciousness, and emotion/affect, and b) distinguish cognitive deficits that are due to isolation and reduced sensory stimulation *per se,* and not attributable to mental fatigue and stress as a result of sleep disturbances or workload. For example, Suedfeld (2010) claims that sensory deprivation experiments claiming cognitive deficits were flawed, and that there are very few well-documented effects of sensory deprivation on cognition.

Cognitive deficits have been reported in some analog environments, and in some space missions. "Winter-over syndrome," is a constellation of symptoms and deficits sometimes reported in individuals who spend the winter at South Pole stations. It includes aspects of impaired cognitive performance, such as impairments in memory, concentration, alertness, increased susceptibility to suggestion or hypnosis, and fugue states (Palinkas, 1989). These changes are potentially attributable to an absence of stimulation in the environment (Palinkas & Suedfeld, 2008) including the absence of exposure to sunlight. There is some evidence that such symptoms increase after the halfway point of a mission ("3rd quarter" phenomenon; Palinkas & Suedfeld, 2008)). During an eighteen-day shuttle mission, various effects were found cognitive skills using the Performance Assessment Workstation, including spatial tracking, spatial matrix reaction time, directed attention and math processing (Eddy et al., 1998). However, some of these effects may have been attributable to microgravity or to a shifted work schedule rather than to sensory stimulation levels.

Several studies have reported specific deficits related to arousal and attention. Reports of winter-over expeditions discuss a phenomenon referred to as “long-eye,” a state of mental blanking in which a person appears to stare off into distant space for long periods (Popkin, Stillner, Osborn, Pierce, & Shurley, 1974). Popkin reports that these episodes were seen in a relatively high proportion of crewmembers (11 out of 50), were strongly associated with leisure time, and were not associated with thyroid deficiencies. An analysis of thought content reveals similarities to daydreaming. The authors suggest that this staring is a “regression from a boring, monotonous, and yet physically threatening environment” (Popkin et al., 1974). A different but related condition termed “drifting” involves more serious lapses of awareness and may involved some forgetting; however, it is unclear to what degree such episodes may potentially be linked with use of alcohol (Popkin et al., 1974).

There are some reports of changes in time perception and estimation during space missions. Astronauts on day four of a six-day shuttle flight were found to overestimate brief time intervals (Ratino, Repperger, Goodyear, Potor, & Rodriguez, 1988), and a study of an eighteen-day shuttle mission found changes in time perception and estimation over ranges of two to sixteen seconds (Eddy et al., 1998). However, a study performed on a different ten-day shuttle mission did not find any effects (T. H. Kelly, Hienz, Zarcone, Wurster, & Brady, 2005).

Other studies of analogs and of spaceflight have failed to find any strong effects. In a Russian experiment on isolation with four crewmembers, nine weeks of isolation was not found to significantly affect work capability, as measured using a variety of cognitive tasks that measured working memory, typing speed, distributed and directed attention, coordination, concentration and reasoning (Gushin, Efimov, & Smirnova, 1996). Indeed, Paulus et al. (2009) claim that studies of prolonged isolation and confinement (e.g. Hockey & Sauer, 1996) do not support the proposition that all individuals in extreme environments experience a deterioration of cognitive abilities. While some individuals do show such effects, others appear able to compensate for performance deficits (though potentially at the cost of increasing stress; Paulus et al., 2009).

While the extreme conditions of spaceflight do not lead to clear deficits in basic cognitive performance (Kanas & Manzey, 2008) more clear effects are seen on resource-demanding tasks during periods of transient adaptation, both in short- and long-duration spaceflight, and during high stress periods that are associated with changes in mood and well-being. An analysis of crew errors revealed an association between errors in tasks and periods of high workload, missed sleep and physical discomfort (Kanas & Manzey, 2008). In a summary of a number of studies that involved shuttle missions, 6- day Mir missions, and a long-duration study of V. Polyakov’s 438-day Mir mission, Kanas and Manzey (2008) suggest that psychomotor tracking performance and situations involving multiple processes (e.g. dual tasks that require divided attention and/or working memory) are most susceptible to the effects of stress and high workload. However, even these deficits can be compensated for in some people.

1.2.2.3 Effects on Affect and Emotion. Adult perceptual systems are in general not very plastic and therefore are largely immune to (the relatively minor) changes in low-level statistics of the sensory environment in a capsule setting. However, as one traverses up sensory hierarchies to association cortices, one encounters greater plasticity, particularly with respect to the meanings and affective responses that come to be associated with specific sensory stimuli (see section 2). It is therefore of little surprise that many of the most well documented effects of isolation and confinement are affective in nature, as a primary goal of affective brain systems is to make appraisals of the environment and one's ability to cope with those changes.

In this section, we review documented effects on affect and mood seen in LDSM analogs that may be attributable to reduced sensory stimulation and monotony, such as boredom, anxiety, stress and more severe mood changes (e.g. depression, asthenia).

Boredom. The visual environment of capsules (and often, their surround) is largely invariant, and that extreme monotony leads to boredom (Suedfeld & Steel, 2000). The Russian Psychological Support Group found that crews started to experience effects of sensory deprivation after the first 2-6 weeks when scheduled work activities decreased and the mission became more monotonous (A. D. Kelly & Kanas, 1994). Effects were countered with increased stimulation and leisure time activities. In a study of the European Space Agency's (ESA) HUMEX & REGLISSE programs, Manzey (2004) proposed that the psychological effects of ICE environments could be classified into four stages. The first stage consisted of an initial, short-term stage of adaptation to the capsule environment and mission that lasted on the order of four to six weeks. Following this initial adaptation, a second stage of six to twelve weeks was observed during which crew members had adapted to the environment, but not yet begun to experience any psychological effects of isolation and confinement. It was during a third stage, after which crewmembers had settled into a routine, that psychological problems as a result of boredom, social monotony and isolation were most severe. Finally, the few weeks before the end of the mission were classified as a separate stage, as crewmembers began anticipating the completion of the mission and re-introduction into wider society. When extrapolating from these simulations to longer missions, it is likely that the first and second stages would remain about the same length, but that the third stage, is likely to be longer and more severe, and that the fourth (anticipation) stage may also begin sooner than on a short mission.

One danger is that the onset of boredom may lead to a self-reinforcing cycle – the lack of meaningful work and sensory stimulation can lead individuals to become less active and decrease their social interactions, which, in turn, reduces sensory variety even more. For example, a bed rest study of pairs of subjects in a room together found that overall, 38% of their time was spent inactive, and that solitary acts became more prevalent over time

(Weiss & Moser, 1998). Even TV watching, a very passive, but still "social" act (given the difficult of ignoring the TV in this setting), decreased over time. (It is unclear if this would still be the case in a setting where individuals were able to watch TV on personal devices.) In its most severe form, boredom in ICE environments may lead to a mental state such as that described above as "long eye" or "staring" (see below), where individuals appear to "zone out" for periods of time that has been observed in Antarctic winter-over missions (Popkin et al., 1974 ; Suedfeld & Steel, 2000). At this time it is unclear whether such states are precursors to more severe disorders.

These studies suggest that for an LDSM to Mars or an asteroid, the most difficult part of the journey is likely to be the period of travel back to Earth, when the crew does not have significant mission elements to look forward to and prepare for. A critical aspect of preventing boredom from setting in is likely to be finding ways to keep astronauts engaged in meaningful work during that period. In an excellent paper on potential approaches for addressing boredom and monotony during LDSMs, Peldszus, Dalke, Pretlove, and Welch (2014) suggests that three critical components need to be addressed through countermeasures: relationship to the system (including meaningful work and science), relationship to the environment (windows, nature), and relationship to other people (communication). We will return to these themes in Section 4.

Anxiety. Although there are a number of documented cases of individuals experiencing anxiety in ICE environments, the number of reported incidences are extremely low, potentially due to the stringent selection criteria imposed on crew selection. In a review of older work on the incidence of anxiety in submarine missions, Kanas and Manzey (2008) found a 5% incidence of psychiatric problems (including anxiety, depression, and psychosis) in one report, 1-2% in another report on nuclear submarines, and less than 1% in a third study. The incidence amongst astronaut applicants is also low, with one study finding that only two out of 223 applicants suffered from anxiety disorder, who would presumably be screened out. However, Kanas and Manzey do note research showing that psychiatric problems, including anxiety disorders, occur more frequently amongst naval personnel at Antarctic stations than at other stations (3% vs. 1%; see Gunderson, 1968), which suggests that screening alone may not necessarily prevent all individuals from experiencing psychiatric symptoms. Note that in all of these studies, it is again difficult to attribute cases of anxiety to reduced sensory stimulation, as opposed to other physical, habitat, or social stressors.

We were able to find one report in the literature of a participant suffering a severe anxiety attack during a complete isolation experiment. The participant, who had successfully completed previous isolation sessions without any problems, experienced an episode of extreme panic a few hours before the end of a three-week isolation experiment that was characterized by a fear of incapability of breathing (Okada, Kinoshita, & Ichikawa, 1996). The participant continued to have additional episodes for several years after the initial episode, and sought therapy to deal with the anxiety, leading the authors to hypothesize that reaction was perhaps the interaction of a predisposition toward anxiety with a disruption of his circadian rhythm. Interestingly, the authors report that the participant, who was aware of the intended length of the isolation, mistakenly thought that the end of that period had been reached. This highlights the importance of giving individuals in ICE environments full and complete information on the expected duration of their isolation.

Stress and Coping. It is clear that ICE environments like those experienced during spaceflight are high stress environments (Sipes & Ark, 2005), and that no astronaut, no matter the selection criteria, is completely immune to the negative effects that stress can have on health, well-being and performance (Suedfeld, 2005). Elevated stress levels such as those observed in polar environments and extreme military environments (training, war zones) can lead to decreased vigor, increased tension, anger, fatigue and confusion (Paulus et al., 2009) which can in turn severely impact mission success. Increasingly, spaceflight research on behavioral health and performance (BHP) is shifting the definition of the characteristics that make a good astronaut (e.g. "the right stuff") away from a rigid personality profile in favor of the view that resilience to stress is the key factor, and that BHP research can lead the way in understanding how to build resilience to stress.

As mentioned in the introduction to this section, stressors can be meaningfully grouped into physical, habitability, psychological, and interpersonal stressors. And while addressing the more obvious stressors such as risk of death and interpersonal conflict are critical to mission success, a number of researchers have highlighted the important link between reduced sensory stimulation and stress. For example, Bartone, Adler, and Vaitkus (1998) suggested five underlying dimensions that have profound effects on variability of performance in extreme environments, including the degree of isolation, ambiguity about the mission, degree of powerlessness, feelings of boredom, and the degree of danger and threat (Paulus et al., 2009).

There is evidence that isolation can lead to a stress response. A French and Russian study of a Russian crew isolated in a pressurized chamber for 240 days found hormonal changes that they suggest potentially reflected decreased sympathetic nervous system activity (Custaud et al., 2004). A 4 month study at the FMARS facility on Devon Island, Canada found that ratings of loneliness over the course of the study showed the highest correlation with stress levels ($r = 0.86$ at month 1, 0.61 at month 2, and 0.90 at month 4), and that the lack of core mission duties for some members contributed to boredom, loss of motivation and apathy (S. L. Bishop, Kobrick, Battler, & Binstedd, 2010). Although reduced sensory stimulation is likely only one component amongst several that may have contributed to feelings of loneliness and boredom, these findings support the idea that sensory stimulation levels (too low, too high, confusing or uninterpretable) can be a potential cause of stress. Suedfeld and Steel (2000) point out that isolation in capsule environments can lead to "information exhaustibility" (pg. 233) and that unstructured time can, in some cases, be experienced as more stressful than overwork, as it provides no distraction from the isolated status of the crew. They caution that failing to address the stresses of monotony and boredom can lead individuals to initiate risky coping behaviors that may endanger the mission. In fact, Kanas et al. (2009) go as far as to suggest that monotony and boredom (from low workload, hypostimulation and restricted social contact) are potentially the most severe stressors likely to be encountered during LDSM. Neurobiological explorations of a link between reduced sensory stimulation and stress will be further explored in Section 2.

In addition to understimulation playing a role in *causing* stress, sensory stimulation can also play a role in coping mechanisms for dealing with stress. Coping mechanisms are responses that are intended to reduce the negative physiological and psychological consequences of a stressor, including disruptions to homeostasis and negative affect. Coping strategies can be generally classified as either being problem oriented (task coping, e.g. "what can I do to reduce this stressor?") or emotionally oriented coping (e.g. "how can I reduce my negative response to this stressor?"; S. L. Bishop et al., 2010). Sensory stimulation can form a part of problem oriented coping strategies if the stressor being addressed is boredom and monotony. For example, during a 135-day, three person simulation of a Mir mission (HUBES), isolation was not a key concern for individuals who were more engaged with recreational activities, family and work (Rosnet, Cazes, & Vinokhodova, 1998). The authors suggest that in stressful situations, the *appraisal* of the stressors is more important than the stressors themselves. Similar to findings from ground-based experiments that increasing crew autonomy over mission management improved mood and lowered cortisol and beta-amylase (Roma et al., 2013), the availability of options for coping with low sensory stimulation levels and the ability to make active choices to increase sensory stimulation is likely to increase the appraisal of one's ability to cope, and therefore affect "situational meaning" (Paulus et al., 2009) in a positive way.

Sensory stimulation can also be part of an emotionally oriented coping strategy in the form of "escapism" from an uncontrollable stressor (such as the possibility of being hit by an asteroid). However, using sensory stimulation as a distraction may not be beneficial in the long term. In the 2007 FMARS study, S. L. Bishop et al. (2010) found that task coping was associated with better adaptation than emotionally oriented coping. Poor coping strategies were correlated with negative mood, and the use of poor coping strategies in the early part of the study predicted stress in later parts of the study (S. L. Bishop et al., 2010). In the more recent Mars-105 study, "disengagement" oriented coping strategies were found to be positively correlated with depression scores, whereas "mature defenses" were positively related to positive emotions (Nicolas, Sandal, Weiss, & Yusupova, 2013). They also found evidence of a reduction in emotion regulation over the course of the experiment, and reported lower scores on positive emotion for all participants during the final days of confinement. Interestingly, a study of coping strategies used during submarine missions found that coping strategies were not related to personality characteristics, but rather to achievement motivation and interpersonal motivation (Sandal, Endresen, Vaernes, & Ursin, 1999)

These results suggest that the development of potential countermeasures for reduced sensory stimulation may need to balance the availability of sensory stimulation countermeasures with the potential for these countermeasures to be used as a form of escapism from ever-present stressors, a potentially unhealthy strategy. In space, however, some stressors cannot be addressed in a problem-oriented way, and so some degree of emotional coping (including reappraisal, acceptance and distraction) may be necessary.

Changes in Mood and Well-Being. Spaceflight can be an exhilarating, peak experience, and can also be a stressful, monotonous experience. Regardless of how well prepared a crew is, long-duration spaceflight is going to affect crew mood in both positive and negative ways.

Very few studies have directly assessed changes in ones' ability to experience pleasure, happiness and joy in a spaceflight setting, though anecdotal reports suggest that space missions, for many, are some of the most joyful experiences of their lives, and the beneficial (salutogenic) effects of spaceflight have been noted by a number of people (see below). However, the potential for negative mood disturbances and more severe depression during spaceflight has been recognized since the early days of the Russian space program, and a number of studies have reported on changes in mood over the course of missions and analog studies.

Although sensory restriction has been identified as having a negative impact on psychological well-being of mission personnel (Suedfeld & Steel, 2000) very little has been done to tease this apart from social isolation and confinement. Given evidence from early studies on sensory deprivation that the addition of another person to an isolated environment drastically reduces the incidence of severe mood disorders, and the low incidence of observed effects in modern space programs, some authors have claimed that expecting severe effects from sensory deprivation during LDSM maybe not realistic (Suedfeld, 2010). Indeed, more recent reports of severe depression or anxiety are rare. This could reflect either an actual low incidence or a failure to detect and report cases, as one potential effect of monotony and reduced sensory stimulation is decreased communication with mission control (fewer contacts, more filtering), which could mask the development of medical and psychological problems (Kanas et al., 2009).

However, it is likely that there is an important distinction between short and long duration spaceflight, and between missions with small and large crews. For example, while it is not the case that many negative consequences have been reported in short-term spaceflight or in submarine crews during periods of isolation (1.9 non-psychotic mental disorders per 100 person-years at sea; Thomas et al., 2003), a higher incidence of mood disturbances have been reported amongst Antarctic winter-over crews (Palinkas & Suedfeld, 2008; Suedfeld & Steel, 2000). In one case that has been reported, an astronaut beginning an LDSM developed symptoms of clinical depression, reportedly due to isolation and separation from his family (Kanas et al., 2009). Fortunately in this case, the symptoms appeared to resolve as the astronaut adjusted to life on orbit and did not develop into a persistent depression.

Some authors suggest that Antarctic winter over crews, and particularly the early polar expeditions, are our best source of information on the likely conditions that an LDSM crew would experience. In a review of older polar expeditions, Palinkas and Suedfeld (2008) state that on many early expeditions (e.g. the Belgica expedition, 1898-99; the Greely expedition, 1881-84), the entire crew would suffer from some form of depression or melancholy. They also mention one case of severe schizoaffective disorder that occurred at a polar station in 1957-58, mention anecdotal reports of "fugue" states of extreme confusion, and cite the previous research mentioned above showing that psychiatric disorders are three times as likely for Navy personnel in Antarctica than those at other stations. Indeed, depressed affect is one of the most common symptoms of people on polar expeditions, closely followed by anxiety and irritability. Over half (62.1%) of the residents at McMurdo Station in 1989 reported feeling depressed, and 47.6% were more irritable than usual. And while this negative affect is generally transient and the symptoms rarely lead to clinical intervention (psychiatric disorders account for only 1-5% of all station sick calls or outpatient visits at research stations), these increases in depressive symptoms in Antarctica are clinically and statistically significant. In the 1995-1997, 5.2% of individuals in the US Antarctic program fulfilled DSM-IV criteria for at least one psychiatric disorder, which, while lower than the general population, is significant in this well-screened group of individuals. Similar to subsyndromal seasonal affective disorder, Palinkas & Suedfeld suggest that many winter-over crewmembers suffer from a "subsyndromal" form of depression.

In a study of 121 winter-over members of the 1988-1989 US Antarctic program, Palinkas and Browner (1995) used a questionnaire to measure depression before the beginning of the winter and again after approximately 1 year. Eighteen symptoms were identified as relevant for depression, and personnel were asked to indicate how much they had experiences these symptoms during the previous month. The symptoms included feeling depressed, loss of energy, fatigue, tiredness, and loss of interest. At time T_0: zero of 91 respondents were classified as depressed; at time T_1 one year later, five of 89 respondents fit the definition of depression. In addition to the increase of depressive symptoms, the researchers found an increase in avoidance as a coping method, and emotional discharge as a coping resource, and these forms of coping were associated with depression. Depressive symptoms at T_0 predicted depressive symptoms a year later. Interestingly, depression was predicted by negative life stressors, decreased self-confidence, and avoidance coping, but not with individual personality measures, social, demographic or psychosocial measures. This led the authors to suggest that coping is "more strongly associated with environmental conditions that influence the severity of stressors and availability of coping resources" than with personal characteristics and background (Palinkas & Browner, 1995). They actually suggest that most Antarctic winter-over personnel experience some aspect of winter-over syndrome, and list as salient stressors events at home, lack of support and understanding from the outside world, a lack of privacy, boredom and emotional deprivation, and the absence of status hierarchies.

Although it is difficult to know how much of these depressive symptoms are directly attributable to reduced sensory stimulation, monotony and isolation, there are suggestions of a strong contribution. Members of the Footsteps of Scott expedition expressed that "the stress we felt on the Barrier was perhaps due as much to the deprivation of the landscape as it was to the uncertainty of what lay ahead" (Palinkas & Suedfeld, 2008). However, there is also some suggestion that depressed mood at Antarctic stations is inversely associated with the severity of the station environment (Paulus et al., 2009).

Individuals experience fluctuations in their mood states, which may depend to some degree on an individual's appraisal of their exposure to isolation, confinement, and an extreme environment (Paulus et al., 2009). There is some evidence of a "3rd quarter effect" in polar environments (Leon, Sandal, & Larsen, 2011), but these findings are highly variable and may depend on the degree of comfort of accommodations. Previous work has documented negative behaviors in the 1st quarter and a decline in both positive and negative mood during the midpoint, while other studies have found increasing mood over course of a short expedition, and general positive mood over the course of a trek (Leon et al., 2011).

Some hints of changes in mood have been found in long-duration isolation analog studies. During the Mars-105 experiment, positive emotion (as measured with PANAS) decreased over the course of the experiment, though self-report measures of depression did not (Nicolas et al., 2013). In this simulation, individuals who pursued "active" and "open" communication strategies had higher mood scores (Gushin et al., 2012). During the Mars-500 experiment, reduced facial expressivity was noted at the halfway point of the mission (Tafforin, 2013), average scores on the Beck Depression Inventory (BDI) peaked in the 3rd quarter of the mission (Basner et al., 2014), and one participant in particular had consistently elevated BDI scores throughout the mission that were correlated with a host of other mood disturbances, physical exhaustion, rated stress and perceived conflict (Basner et al., 2014).

A bed rest study in which participants spent three days lying in bed with a 6° downward head tilt found higher depression scores (Beck Depression Inventory) when compared to participants that were horizontal (Styf, Hutchinson, Carlsson, & Hargens, 2001), potentially due to increased body discomfort (back pain, abdominal pain, headache, leg pain). A different study reported that over the course of a 42-day period of (6° downward) bed rest, pairs of participants in rooms together showed signs of social withdrawal, increasing their number of solitary acts (Weiss & Moser, 1998).

Together, these studies suggest that while the overall prevalence of clinically relevant changes in mood in ICE environments may be relatively rare, subclinical changes in mood during long periods of isolation and confinement are quite common, and present a significant risk for LDSM. These symptoms occur in individuals who are part of small, medium, and large groups, in situations of high workload and in situations of low workload. Although further research will be needed, this pattern is consistent with a role for reduced sensory stimulation and monotony in these mood changes.

Asthenia. The Russian space program defines asthenia as "nervous or mental weakness manifesting itself in tiredness... and quick loss of strength, low sensation threshold, extremely unstable moods, and sleep disturbance. Asthenia may be caused by somatic disease as well as by excessive mental or physical strain, prolonged negative emotional experience or conflict" (7, p. 28)." (taken from Kanas et al., 2001). The Russian space program sees asthenia as a serious issue that represents a "frontier" between health and disease. They use a number of countermeasures for it, including allowing more leisure time, changing job scheduling, encouraging physical activity, sending surprise gifts to provide novelty and stimulation, and improving morale by increasing audiovisual contact with Earth.

Although asthenia is not recognized by the American Psychiatric Association, the cluster of symptoms it describes would be variously categorized as symptoms of adjustment dysthymic, or major depressive disorders, or chronic fatigue syndrome, and a number of American astronauts have reported symptoms suggestive of asthenia (Kanas & Manzey, 2008).

Using the Profile of Mood States (POMS) questionnaire Kanas et al. (2001) asked Russian psychiatrists to answer the questionnaires as if they were experiencing asthenia, and additionally highlighted eight test items that were seen as characteristic of asthenia. POMS responses for five astronauts and eight cosmonauts aboard space shuttle and Mir missions (over a four and a half year period) were then scored on these items. No evidence of asthenia was found for any of the astronauts (17-19 weeks in space) nor for any of the cosmonauts (25-29 weeks in space). However, one major drawback of this study should be mentioned, which is that the data was averaged over all mission weeks, and therefore would be less sensitive to symptoms that developed as a result of long durations in space.

Earth Out-of-View. Several researchers have raised the possibility that LDSM may present a unique challenge for astronauts on account of the fact that the visual connection with Earth, which is highly salient in LEO, will be lost (Horneck et al., 2006; Suedfeld & Steel, 2000). Although there is clearly no research on this phenomenon, it does raise some interesting questions. While it seems unlikely that the physical sight of the Earth is really the issue (planet-bound individuals do not "see the Earth" but only local patches of it), it is possible that a need for a psychological *connection* to the Earth may be of central concern. Such a need could potentially be met through adequate communication countermeasures that allow an astronaut to feel as if they are still a part of the earthbound community.

Salutogenesis. A primary reason that humans engage in exploratory activity is because of the expectation that the journey itself, and not just the potential financial or social outcome, will be rewarding. Over half a century of human spaceflight has proven these expectations correct – the vast majority of astronauts report that their journeys in space have been among the most (if not the most) rewarding and exhilarating moments of their lives. Such positive effects of spaceflight are referred to as salutogenesis, and have been reported for polar expeditions as well (Palinkas & Suedfeld, 2008).

Although there is no research on this to date, it seems likely that there may be a relationship between sensory stimulation and salutogenesis. As will be reviewed in Section 2, aesthetic experiences with artwork have the potential to be strongly moving. It is possible that aesthetic experiences, such as the awe and sublimity of seeing a view from a mountaintop or from the ISS, may share something in common with other inspirational brain states and "flow states," and may even contribute to the salutogenic effects of exploration missions. Indeed, Suedfeld highlights the connection between aspects of spaceflight and flow states, which involve ""intense and focused concentration on one's activity that merges action, awareness, and a feeling of working at one's best that becomes intrinsically rewarding" (Suedfeld, 2005). Interestingly, in a study on salutogenic effects reported by 39 astronauts and cosmonauts who have flown at least one space mission, "perceptions of the Earth" were the one aspect of personal growth that showed a significant change as a result of spaceflight (Ihle, Ritsher, & Kanas, 2006). The degree to which this is directly attributable to visually experiencing the view of Earth from space remains to be seen.

1.2.3 Individual Differences. A number of studies have highlighted the importance of understanding and measuring individual differences in suitability for, and reactions to, long-duration spaceflight. Differences in skills, personality, tastes and problem-solving style can have serious in-flight consequences. For example, different individuals may use very different strategies to solve a task and even compensate for a lack of aptitude in one area, resulting in higher fatigue (Paulus et al., 2009). In a recent analysis of the MARS-500 mission simulation project, Basner et al. (2014) reported large inter-individual differences in ratings of mood disturbances, stress and physical exhaustion on the Profile of Moods State (POMS) measure that correlated with highly mission relevant behaviors, such as the persistent presence of depressive symptoms and participation in perceived conflicts (Basner et al., 2014).

Not only are different people likely to be more or less able to cope with reduced sensory stimulation, isolation, and monotony over long periods, but sensory stimulation countermeasures may also need to be tailored to the specific sensitivities and tastes of individual crewmembers. For example, individuals in polar environments tend to decorate their own crew quarters in unique and personal ways, using photographs, plaques, paint and decorations (Suedfeld & Steel, 2000)

Several groups have sought to relate such individual differences to existing models of personality. Suedfeld and Steel (2000) suggest that the "big 5" personality traits have good face value for selection, with higher than average scores on conscientiousness and agreeableness being positive selection criteria, neuroticism being a negative selection criterion, and openness to experience and extraversion being of mixed usefulness. Openness to experience is potentially a mixed predictor of success on LDSM missions given the fact that a person is embarking on a highly novel journey, but that success on the mission may critically require on a person to restrain from brash, unsafe sensation seeking. Suedfeld suggests extraversion should be considered a mixed predictor for LDSM success since the ideal candidate for capsule living would enjoy, but not need social interaction (Suedfeld & Steel, 2000). In their analysis of polar expeditions, Palinkas and Suedfeld (2008) mention that older research had identified age, education and occupational status, extraversion and neuroticism as predictive risk factors for psychiatric disorders in polar expeditions (with high extraversion and neuroticism associated with higher risk). However, Leon et al. (2011) reviewed work that found higher than normal degrees of openness to experience in polar work groups, and that well adapted polar workers in fact scored higher on Openness to Experience, in addition to scoring higher on Emotion-Focused Coping. She also reports findings that Antarctic technical personnel generally have a lower need for stimulation, and that workers in a range of jobs that were rated highest in performance had low scores on measures of neuroticism, boredom, need for order, affection from others, and achievement motivation (Leon et al., 2011).

However, in some cases of ICE environments, personality characteristics have failed to predict important aspects of behavior and performance. A study of coping strategies used during a 10-day and a 40-day submarine mission found no straightforward relationship between personality characteristics (measured using the Personality Characteristics Inventory [PCI] developed at NASA) and coping strategies (Sandal et al., 1999). Rather, they found that an interpersonal orientation and achievement motivation did predict use of positive coping strategies. And despite highlighting earlier research showing some predictive relationships on polar expeditions, Palinkas and Suedfeld (2008) suggest that baseline personality traits generally have little ability to predict behavior and performance, as such volunteers are generally highly motivated and vary less on personality traits than the general population.

These contradictory findings are likely related to what has been termed the "personality paradox" – individuals who volunteer for spaceflight, polar expeditions and submarine missions tend to be those who would score on the high end of any thrill- or sensation seeking scale, as well as measures of competence motivation, as these tend to be people who want adventure and challenge. Yet these individuals then discover that these missions are oftentimes tedious and boring, and involve work in monotonous and isolated environments that offer no escape. How to select for individuals who are both up for a challenge but able to tolerate monotony and loss of personal autonomy remains an open issue.

1.3 SUMMARY

Research on Sensory Deprivation in Animals and Humans

- Although research on complete sensory deprivation is not directly analogous to conditions during long-duration space missions (LDSM), the literature is still useful for understanding the potential mechanisms underlying changes observed in an environment of altered/reduced sensory stimulation
- Most studies of sensory deprivation in humans are more than several decades old. Studies of sensory deprivation in animals, and more recent studies of sensory deprivation in adult humans reveal that plasticity is present in adult human sensory systems, even for functions that were previously thought to be static. Sensory deprivation can lead to either hypo- or hyper- sensitivity depending on whether there is competing input present. Changes can happen in as little as two days. Complete sensory deprivation does not render a brain region inactive. A balance of inhibition and excitation normally maintain a homeostatic mean firing rate, which may be perturbed by reduced sensory stimulation.
- Animals in minimal, isolated environments exhibit abnormal behaviors, anxiety and stress. Enriching the environment with the presence of other animals, variety, complexity, exposure to natural elements, sounds and smells, and opportunities for play can counteract such effects.
- The presence of continuous noise can lead to the destabilization of auditory-vocal feedback circuits, disturbing song production in birds.
- There is a useful distinction between "low-level" effects versus "high-level" effects.

Analog Studies: Perception

- A variety of analogs exist for studying the effects of reduced sensory stimulation in isolated, confined and extreme (ICE) environments
- Much of the research on analogs and extreme environments has focused on the "extreme" nature of the environment (cold, hazards, etc.) or on the social aspects. There has been very little work that separates out the sensory effects from other effects.
- There are a variety of short-term perceptual deficits experienced during adaptation to microgravity, but very few documented effects on perception beyond this adaptation period. There are some reports of changes in perceptual sensitivities, but little hard data. There are anecdotal reports of hallucinations, but generally little evidence.
- The effects of changes in light exposure are salient and well known.
- A recent study of the Mars-520 experiment found no effects on depth perception, though it is possible that some flaws may exist in their design. This is in contrast to

reports that Navy sailors have reported effects on depth perception of long-term confinement in small spaces.
- There is some evidence that systems for motor-visual interaction (e.g. reaching movements) may be more susceptible to changes in sensory stimulation.
- Taste and smell undergo changes as a result of fluid shift and congestion.

Analog Studies: Cognition

- The effects of reduced sensory stimulation on cognition in analog environments are difficult to distinguish from effects of fatigue, and from effects on arousal and affect.
- The evidence for cognitive effects is mixed. However, there is some evidence for effects on spatial tracking, speeded reaction times, directed attention and math processing. There is stronger evidence to support the claim that resource-demanding tasks are generally affected in extreme environments, particularly during adaptation periods.
- "Winter-over syndrome" in Antarctic crews includes a number of cognitive impairments (memory, concentration, alertness, "long-eye"), and these issues may get worse during the second half of the isolation period ("3rd quarter" phenomenon).
- There is some evidence for changes in time perception.

Analog Studies: Affect and Emotion

- Boredom is well documented in environments of reduced sensory stimulation, and represents a high potential risk. Chronic boredom may be a precursor to more severe affective disturbances.
- Despite anecdotal reports, very few cases of severe anxiety are observed in ICE environments, potentially due to screening procedures. However, the incidence is higher in isolated compared to non-isolated environments. Accurate information about the passage of time may help alleviate anxiety.
- Isolation and reduced sensory stimulation can lead to a stress response.
- Sensory stimulation can also form a part of a strategy for coping with stress. A distinction should be made between the uses of sensory stimulation in problem-oriented coping and "disengagement" oriented coping strategies.
- Spaceflight can be a source of extreme positive mood (salutogenesis) as well as of negative mood. Little information is available on the role of reduced sensory stimulation on mood (as separate from social isolation).
- Reports of severe mood disturbances during spaceflight are rare, but potentially underreported, and may be more of an issue for long duration missions.
- Reports of subclinical disturbances in mood during Antarctic winter-over expeditions and other ICE environments are more common. Personality characteristics do not appear to predict susceptibility to depression, while coping strategies do show some relationship.
- Evidence for asthenia is lacking.

Analog Studies: Individual Differences

- Measuring differences in personality may be very important for selection. While some groups have claimed that extraversion and neuroticism are associated with higher risk for psychiatric disorders in ICE environments, the evidence is mixed. Differences in coping strategies may be a better predictor.

SECTION 2: HOW REDUCED SENSORY STIMULATION AFFECTS PERCEPTION, COGNITION, AFFECT AND MOOD

Framing Question: What processes mediate the link between sensory stimulation levels and observed changes at different levels of analysis, and how can understanding these processes help guide the creation and evaluation of countermeasures?

An evaluation of the effectiveness of proposed countermeasures for augmenting sensory stimulation will benefit from an understanding of the mechanisms by which reduced sensory stimulation and monotony affect astronauts' abilities to perform mission-critical duties, both in the short-term and over the course of a long-duration mission. This theoretical framework can be used to generate specific target constructs for intervention and also guide the development of methods for measuring the effectiveness of proposed countermeasures.

This section will summarize a large body of neuroscientific and psychological research to provide theoretical links between sensory stimulation levels and potential effects on perception, cognition, affect, emotion and well-being. This will include a look at how sensory stimulation levels affect stress, coping and resilience.

2.1 LOW-LEVEL EFFECTS

Neural plasticity affects multiple levels of the nervous system. The weakening or strengthening of synapses is involved in subtle shifts in sensitivity of localized circuits, as well as the formation of new associations across multiple cortical columns and the encoding of new episodic memories in the hippocampus.

One primary mechanism for synaptic plasticity occurs at synapses that use the neurotransmitter glutamate, and involves changes in the number of a type of receptor molecule on the postsynaptic neuron (AMPA receptors) as a result of specific (high frequency) patterns of excitation of the neuron (Malenka & Bear, 2004). These patterns of excitation are detected by NMDA receptors, which are voltage sensitive, and lead to trafficking of new AMPA receptors to the post-synaptic membrane.

Synaptic plasticity can occur in all regions of the cortex. However, the regions of the cortex that receive initial input from sensory receptors (e.g. the eyes, ears, touch receptors; typically conveyed via the thalamus) are less plastic (changeable) in adulthood. In these regions, the patterns of connectivity between neurons form efficient networks for encoding the stimulation patterns that occur in the environment and transmitting this information to higher levels of analysis. By adulthood, these coding mechanisms are well matched for the statistical properties of the sensory environment, and changes are uncommon.

In vision, for example, the early stages of perceptual analysis represent the sensory environment in a retinotopic fashion (i.e., with respect to the topographical layout of the retina). Individual neurons in V1, the first cortical region to receive visual input, are sensitive to the presence of oriented luminance contrast (light/dark patterns) in small, local patches of the visual field that range in size from a half of a degree of visual angle at the fovea (the part of the retina that receives light from the very center of gaze) to at most several degrees of visual angle in the periphery (Hubel & Wiesel, 1962; Kamitani & Tong, 2005; Olshausen & Field, 1996). A characterization of the size and nature of the part of the visual environment that a neuron responds to is referred to as the neurons *receptive field*. The concept of a receptive field is also used in other sensory domains to describe, for example, the set of auditory frequencies that a neuron in the auditory system responds to, or the patch of skin to which a neuron in the somatosensory (tactile) system responds (Jay & Sparks, 1984; Kaas, 1991).

If the statistical properties of an aspect of the sensory environment change, these brain regions supporting early stages of perceptual analysis can in fact show plastic changes. Such changes are generally referred to as forms of statistical learning or perceptual learning.

Adult perceptual systems can also support long-term enhancements in the ability to perform specific tasks as a result of visual experience over the timecourse of days, weeks, or years (perceptual learning). For example, an X-ray specialist learns to detect and distinguish fine visual patterns over repeated exposure to images of healthy and injured or diseased tissue, and a piano tuner learns to discriminate extremely fine differences in pitch that may not be discriminable to most people. These plastic changes can be a result of both conscious and implicit processing – while conscious attention to a feature can enhance perceptual learning, detection of *unattended* features can also be enhanced in situations where those unattended features are not explicitly detected and suppressed (Sasaki, Nanez, & Watanabe, 2010). The general picture that emerges from the perceptual learning literature is that there are mechanisms in the cortex for "gated" plasticity, where attention or reinforcement can signal regions of perceptual systems (and their connections to regions that support decision-making) to change in response to repeated exposure to even very subtle cues below the level of awareness (Sasaki et al., 2010). These changes can often be very local and specific (e.g. to one part of the retina), but have also been found to generalize in some circumstances to other locations or features.

No research has directly explored whether the altered statistics and regularities of an isolated and confined sensory environment lead to forms of statistical and perceptual learning. Yet these literatures highlight the fact that adult perceptual systems maintain plasticity and will exploit and adapt to perceptual regularities. Whether such changes are purely adaptive, or could, in certain circumstances, prove to be maladaptive (e.g. in the shift from a transit capsule to a surface habitat), is not known.

2.2 COGNITION

The nervous system can be understood as consisting of perception-action cycles at multiple levels of abstraction. At the lowest level, sensory receptors can form immediate loops with motor neurons to provide simple reflex actions to very specific stimulation. While such actions are simple and fast, they lack flexibility. Multiple higher levels of mappings from perceptual inputs to actions exist that allow for increasingly flexible behavior, but require more computational power and take more time to complete. At the highest level, complex cognitive and metacognitive reasoning can lead to consciously mediated actions that have very little, if any, connection to the sensory environment of a particular moment. Intermediate perception-action cycles also exist that involve varying degrees of automaticity, awareness and intention.

Whereas the term "cognitive" may, in some contexts, specifically refer to levels of representation and action planning that involve "thinking" (conscious reasoning about beliefs, desires and outcomes) and exclude emotional processing, modern cognitive psychology and cognitive neuroscience generally use the term "cognition" to refer to cortically mediated perception-action loops, regardless of whether the processes and representations involved reach conscious awareness, are under volitional control, or involve processes one may call emotional.

In this section, we will outline aspects of perception, recognition, attention, memory, executive function, and conscious awareness that are relevant for understanding the potential effects of sensory stimulation on these cognitive processes.

2.2.1 Perception and Recognition. Perception and recognition are a set of processes for taking the output levels of sensory receptors and transforming them into increasingly abstract representations that allow for more flexible behavioral responses. At each stage of transformation, the resulting representation may be well suited for a particular type of learning and association with action plans. For example, a bright flash or loud sound can be detected at a very rudimentary level of representation, and that representation is sufficient for guiding an appropriate orienting response. Yet this level of representation would be insufficient for detecting a snake in nearby grass, as there is no low-level cue that can uniquely signal the presence of a snake. Feature extraction and segmentation of foreground from background, two key processes that would allow for the detection of a snake, require more complex computational processes. Following these processes, a rudimentary representation of a snake could then come to be associated with a stereotyped behavioral response, such as freezing. However, even this level of representation may be insufficient for distinguishing a snake from a garden hose, or for knowing that a snake in a cage at the zoo poses no threat – this level of adaptive behavior requires even more complex processes of abstraction, including object recognition, semantic access, and the combination of this information with situational awareness and goal states.

The example presented above of identifying a snake on the basis of simple visual properties that are segmented from the background represents an instance of what is termed a “fast” route to action (Kahneman, 2011; LeDoux, 1996). Although slower than a simple reflex, such responses to visual objects are fast, unconscious and relatively simple in that they can be easily tricked (e.g. by a garden hose). This is in contrast to the comparatively “slow” route to action that is mediated by highly flexible and robust representations of objects and events that support access to explicit semantic information (naming) and conscious reasoning about appropriate actions.

2.2.1.1 “Bottom-Up” Hierarchical Perceptual Processing. The “slow” route contains many representations of the sensory environment in different forms, and is characterized by both a) divergent neural connections that separate different features into different maps and b) convergent neural connections that support synthesis over sets of local features for the detection of more complex features. The combination of divergent and convergent connections supports the development of representations that possess a degree of *invariance*, which is a functionally useful loss of sensitivity to some feature of a stimulus. For example, it is useful to know if someone is saying one’s name, and people learn to recognize their own name (and many, many other words) even if an individual who they have never met before is speaking it. Despite the fact that the low-level acoustic properties of the utterance are entirely different from any previous utterance of one’s name, the auditory system is able to extract invariant features from the audio input that can be reliably mapped onto an internal representation (“my name”) and affect action planning.

In the visual system, the extraction of invariant features from retinal stimulation is thought to largely proceed along two major pathways (Goodale & Milner, 1992). The *ventral visual pathway* proceeds anteriorly from V1 (the first cortical region to receive input from the retina via the thalamus) along the ventral (inferior) surface of the cortex and into the temporal lobe. This pathway, often referred to as the “what” pathway, extracts invariant shape features that support identification of objects and places, allowing access to semantic labels and associations. From V1, the ventral visual pathway proceeds through cortical regions V2, V4, several lateral occipital regions (LO), and into occipitotemporal regions of the fusiform gyrus, the collateral sulcus of the inferior temporal lobe, and the parahippocampal gyrus, where it interfaces with the medial temporal lobe fields of the hippocampal formation through the perirhinal and entorhinal cortices (Murray, Bussey, & Saksida, 2007; Van Essen, Anderson, & Felleman, 1992). The anterior regions of the ventral visual pathway also project to several other brain regions, including the ventral striatum and the orbitofrontal cortex (Murray et al., 2007; Rolls, 1999).

The second major cortical visual pathway, the *dorsal visual pathway*, proceeds dorsally (superiorly) from V1 and into the parietal cortex. This pathway is referred to as the “where” pathway or sometimes the “how” pathway, and is important for extracting invariant position and shape features that support interaction with an object, such as walking, reaching and grasping (Goodale & Milner, 1995). From V1, the dorsal visual pathway proceeds through cortical regions V2, V5/MT, MST, and into regions of the inferior parietal sulcus, where it interfaces with parieto-frontal networks supporting spatial attention and action planning. The dorsal visual pathway also sends projections to the medial temporal lobe, and the two systems interact extensively at multiple points along these processing hierarchies.

Similar pathways have been found in auditory regions of the brain that support separable analyses of "what" a sound is versus "where" a sound is coming from (Romanski et al., 1999). Indeed, the extraction of increasingly invariant representations that are useful for highly flexible action planning appears to be a general property of all sensory systems, and extends to the combination of information from different sensory modalities that jointly contribute to object identification and action planning.

A consequence of this organization of perceptual pathways is that there is not just one representation of the sensory environment, but many representations at different levels of abstraction. Long-term changes in the sensory environment, as would be experienced during LDSM, can be classified in terms of how they affect activity at these differing representational levels. Sensory deprivation (SD) is a complete lack of sensory stimulation at all levels. Perceptual deprivation (PD) is characterized by the presence of sensory stimulation at early sensory stages (e.g. retina, thalamus, and possibly even V1) but that is not organized into any coherent structure, resulting in a lack of activation of higher-level stages of perceptual analysis. Sensory monotony may be thought of as a situation where there is sensory stimulation at multiple levels of the sensory hierarchy (e.g. low level stimulation, as well as the presence of edges, surfaces, shapes), but a lack of activation at the highest levels of sensory representation as a result of habituation mechanisms to an unchanging environment (see discussion of repetition suppression in *Section 2.3.2.2*).

***2.2.1.2 "Top-Down" Modulation*.** However, there exist more than just "feed-forward" connections from simpler maps of features to more complex maps of features. At all levels of representation, predictions about what is *expected* in the environment on the basis of previous experience affects the activity of lower levels of analysis – that is, brains are "world modelers" (Churchland & Sejnowski, 1994). Higher-level models of the sensory environment bias earlier perceptual mechanisms through feedback ("top-down") pathways. These top-down connections support task-specific goal-directed attention and expectations, as well as aspects of mental imagery.

2.2.2 Attention. Attention refers to a set of processes that are involved in the selective processing of some stimuli and filtering of others. It is generally divided into *exogenous* attention and *endogenous* attention. Exogenous attention refers to attentional "capture" by salient external stimuli, such as bright flashing lights, vivid patches of color, motion, or loud sounds. Endogenous attention refers to top-down deployment of attention to locations or objects in the environment in the service of goal-oriented behaviors, such as searching for a face in a crowd or reaching to pick up a cup. In the visual domain, such attention can involve directly fixating that location (overt attention) or not (covert attention).

In the absence of sensory stimulation, there may be fewer things in the environment that capture attention exogenously. One result of this may be a shift in the balance between endogenous and exogenous attention. Endogenous attention, sometimes referred to as directed attention, requires greater effort to maintain over a long period of time (Knudsen, 2007). A consequence of this shift, then, may be increased effort to maintain attentional focus, and increased mental fatigue.

The voluntary deployment of attention is correlated with activation in a network of brain regions that includes the inferior parietal sulcus (IPS) and the frontal eye fields (FEF; "dorsal attention network"), while stimulus-driven reorienting of attention (e.g. following an invalid cue) is correlated with activation in a separate, right-hemisphere biased network ("ventral attention network") that includes the temporo-parietal junction (TPJ) and inferior frontal gyrus (IFG) (Vossel, Geng, & Fink, 2014).

2.2.3 Memory. There are multiple forms of memory that serve different functions, including working memory (see *2.2.4 Executive Function*), short-term memory and long-term memory. Memory can generally be divided into those forms that are "implicit", such as sensory and perceptual memory, priming, and procedural (skill) memory, and those that are "explicit", such as episodic and semantic memory.

Although there is very little work that has explicitly investigated the role of sensory stimulation on memory in humans, sensory stimulation levels could potentially affect memory in at least two ways. First, memory may be affected indirectly via stress, fatigue, or a lack of attentional resources as a result of an impoverished sensory environment (see *2.3.4 How Sensory Stimulation affects Stress and Coping*). It is known that both stress and a lack of attention can affect consolidation (Schwarze, Bingel, & Sommer, 2012; Talmi, Schimmack, Paterson, & Moscovitch, 2007), and that stress and fatigue can also negatively affect recall (Kuhlmann, Piel, & Wolf, 2005). Stress may also suppress neurogenesis in the hippocampal formation (J. J. Kim & Diamond, 2002), which may in turn result in fewer neural resources being available for the formation of new memories. Second, it is also possible that events that contain less sensory variety may be more poorly remembered than similar events with more sensory variety. Emotional content is known to improve memory encoding (LaBar & Cabeza, 2006), and objects with a greater number of associations are also better encoded (Mayes, Montaldi, & Migo, 2007). Rich sensory experiences are likely to both be more emotional and engender more associations.

Memory also plays a role in mediating the role of sensory stimulation on emotional and semantic responses – the detection of novelty and familiarity (see below, *Section 2.3.2.2*) rely on forms of memory, and the number of semantic associations brought about by a sensory experience is dependent on past experience and associative recall. As a result, it is possible that the interaction of reduced sensory stimulation and memory may contribute to a detrimental cycle of feedback - new memories formed during a period of reduced sensory stimulation may result in episodic and semantic memories with fewer associations, which would make them more difficult to encode and recall. Future experiences that then re-activate portions of these representations would engender fewer rich associations, making those experiences less pleasurable.

2.2.4 Executive Function. “Executive function” refers to a set of cognitive control processes that manage the implementation of goal-directed behaviors; namely working memory, reasoning, task flexibility/switching, and problem solving. The effects of reduced sensory stimulation and monotony on executive function are not well characterized, and to date there is little evidence to suggest that reduced sensory stimulation has any direct effect on cognitive control. It is likely that any effects would be mediated through depletion of attentional resources or stress-induced functional impairment. However, it is possible that an unmet information foraging drive (see *Section 2.3.2.1*) may lead to perseverance on potentially risky exploratory behaviors at the cost of effort directed toward other mission critical goal-directed behaviors.

Deficits in working memory capacity will affect a persons’ ability to integrate a sensory experience – watching a movie or reading a book during a period of degraded working memory capacity is likely to result in less pleasure than normal, because not enough information is retained over a short time interval to allow for extraction of higher-level structure and integration into an ongoing understanding.

2.2.5 Consciousness. Under normal circumstances, our sensory environment, or at least, salient aspects of it, occupy a large proportion of our conscious awareness. However, a state of conscious awareness is not dependent on sensory stimulation – an internally focused state of awareness can be a conscious state. Whether or not a prolonged period of reduced sensory stimulation has an effect on general awareness, wakefulness, or the nature of conscious states is entirely clear, though the results of the Mars-520 experiment did find that participants slept more (and were awake less) as the experiment progressed (Basner et al., 2013).

Meditation, which can be thought of as a set of tools for learning to control and manipulate states of consciousness, provides a potentially interesting avenue for research on the link between sensory stimulation levels, conscious awareness, and neural noise. Certain forms of meditation can reduce the rate of alternation between bistable perceptual states, as occurs during binocular rivalry or viewing of a Necker cube (Carter et al., 2005). One potential mechanism for this slowing of switches between perceptual states is through a reduction in internal ‘noise.’ In the absence of normal perceptual stimulation, it is possible that this neural noise may increase, or become more dominant in the face of reduced external input. Meditation may be one way to study the relationship between these potential changes in internal noise, sensory stimulation and directed attention.

2.3 AFFECT AND EMOTION

One of the most serious but least understood risks of long duration spaceflight (and ICE's in general) is the possibility of an adverse behavioral or psychological events, or development of a psychiatric disorder during the mission. The primary neural systems that have been implicated in such disorders are those linked to valuation, affect, mood and decision making. Therefore, a key component for the development of behavioral and psychological countermeasures is to understand the potential effects of a reduced and monotonous sensory environment on affect, emotion and stress.

Humans get pleasure from sensory experiences, from such "simple" pleasures as tasting chocolate or soft touch, to complex sensory experiences such as listening to music, reading a book, looking at a sunset, walking through the woods, or watching movies. As was reviewed in the first section, the lack of access to such sensory experiences is experienced as aversive. Indeed, in every day life, humans seek out these experiences, and are willing to work for (and spend money on) attaining such experiences. Why do humans seek out such experiences, how do they give us pleasure, and why is their absence experienced as stressful? Here, we review theory and evidence for how sensory experiences are linked to pleasure and desire (e.g. incentive salience), two key aspects of reward valuation. We then review ways in which reduced or monotonous sensory stimulation may be linked to emotional states, stress and mood.

2.3.1 Pleasure and Reward Systems in the Brain. A defining component of emotional experiences (that distinguish them from other psychological processes) is that they contain affect. *Affect* refers to positive or negative hedonic experience. The simplest forms of affect are pleasure (positively valenced affect) and pain (negatively valenced affect).

From a vast number of studies in animals and humans, it is well understood that specific stimuli and contexts (patterns, objects, sounds, rooms, people, etc.) can become associated with positive or negative hedonic outcomes through forms of reward learning such as classical conditioning and reinforcement learning (Mackintosh, 1984; see Dayan, 2002 #512 for a review; Skinner, 1938; Thorndike, 1911). These mechanisms allow an organism to predict and respond to biologically important events, such as the appearance of food, conspecifics, or threats. Arbitrary stimuli, such as lights or sounds, can acquire value through association with "primary" reinforcers that have intrinsic value to an animal such as food, water, access to conspecifics, and aversive stimuli such as shocks or air puffs. A good deal is known about the brain mechanisms underlying this type of goal-directed behavior. A full review of this literature is beyond the scope of this report; below we will outline a number of the key structures and theories that are relevant for understanding the effects of reduced sensory stimulation and its augmentation.

Research in animals and humans suggest that there are multiple, separable components of positive and negative valence systems. Positively valenced affect can be separated into at least three components. Core "liking" refers to the immediate hedonic impact (pleasure) experienced during consumption of a rewarding stimulus. On the other hand, "wanting" refers to the motivation or incentive salience to obtain a reward, and is related to anticipatory craving or desire (Berridge, Robinson, & Aldridge, 2009). In addition, there are separate processes that mediate reward-related learning. Similarly, negatively valenced affect is proposed to reflect the operation of systems involved in threat, loss, and coping. Based on the past several decades of research into the neural basis of affect and emotion, the NIH has recently launched an initiative aimed at understanding mood disorders within this neurobiological framework NIH RDoC: framework for linking behaviors and symptomatology to multiple levels of analysis of the nervous system (Insel et al., 2010).

Pleasure is represented at multiple levels in the nervous system, including in the brainstem (e.g. parabrachial nucleus), the striatal and pallidal nuclei of the forebrain, and in the cerebral cortex (Glahn et al., 2010). By studying animals' responses to sweet taste, Kent Berridge, Morton Kringelbach and their colleagues have identified regions in the nucleus accumbens (NA; in the ventral striatum) and the ventral pallidum (VP) that they call "hedonic hotspots" – activation of neurons in larger portions of both of these structures can elicit "craving" or "seeking" behaviors (e.g. wanting), but only activation of neurons in these much smaller "hotspots" elicits "liking" behaviors (e.g. licking). Whereas the "wanting" circuit seems to be heavily dependent on dopamine, hedonic pleasure actually appears to be linked to opioid- and cannabinoid-receptors (Berridge & Kringelbach, 2013; Castro & Berridge, 2014). Direct causation of affect is thought to rely chiefly on these two subcortical structures, which are heavily interconnected and act as a circuit whose activation is both necessary and sufficient for generating pleasure.

The hedonic hotspots of the NA and VP form part of a larger mesocorticolimbic system that support other components of liking, and give a "pleasurable gloss" to rewards of different types. For example, unconscious facial expressions (e.g. smiling, eyebrow raising; (Childress et al., 2008; Winkielman, Berridge, & Wilbarger, 2005) and other behaviors (e.g. licking) associated with pleasure are likely mediated by portions of the hypothalamic "behavioral control column" (see below; Swanson, 2000). In humans, cortical regions are especially important in affect and emotion. (Berridge & Kringelbach, 2013) cite evidence suggesting that the conscious perception of subjective pleasantness and pleasure likely takes place in regions of the orbitofrontal cortex (OFC), particularly the mid-anterior OFC, and that other parts of the OFC also code aspects of pleasure that are relevant for monitoring and predicting reward value.

Importantly, the affective value of a stimulus, both its pleasure and incentive salience, are separable from a representation of its stimulus properties. For example, the same taste, smell, or tactile sensation can be experienced as pleasurable, neutral, or even aversive depending on the behavioral state of the animal. From research on the rewarding properties of food, it is clear that a representation of the sensory properties of a taste or smell is separate from its associated value (Rolls, 1999). Reward values of tastes are encoded in the OFC, where there is also a convergence of visual information from the anterior inferotemporal cortex, allowing for visual-taste associations (Hetherington, Bell, & Rolls, 2000; Rolls, 1999; Rolls, Thorpe, & Maddison, 1983). Recent evidence suggests that the expected value of novel conjunctions of known tastes, such as “tea-jelly,” is encoded in medial-caudal regions of the OFC, independent of stimulus information and reward information about the component items (Klein-Flugge, Barron, Brodersen, Dolan, & Behrens, 2013). It should be noted that there is also convergence of information from other senses in the OFC, such as audition, smell and touch (Hetherington et al., 2000)

The amygdala, a collection of nuclei and cortical fields in the medial temporal lobe, also appears to be an important locus of stimulus-value associations. The firing of neurons in the primate amygdala to the presentation of visual stimuli (e.g. fractals, referred to as a “conditioned stimulus”, CS) is modulated by the reinforced value (positive or negative) that has been associated with each individual stimulus (by pairing with an “unconditioned stimulus”, US, such as air puff or water; Paton, Belova, Morrison, & Salzman, 2006), and this code changes as the stimuli undergo reversals in their associated value (through a change in CS-US pairings).

2.3.2 Linking Perception and Affect. This circuit, including the amygdala, OFC, and their output projections to the ventral striatum and hypothalamus, form the core of a system that represent the value of stimuli that have come to be associated with primary and secondary reinforcers and punishments (Hetherington et al., 2000; Swanson, 2000). These regions get input about the presence of objects and features in the sensory environment from sensory hierarchies, such as the ventral visual pathway, and learn associations to primary reinforcers with the help of “reward prediction error” signals from mesolimbic structures that use dopamine as a neurotransmitter (e.g. the ventral tegmental area, VTA, and the substantia nigra, SN; Schultz, Dayan, & Montague, 1997). The amygdala, which is an evolutionarily older structure, likely represents simpler, less flexible forms of association to specific sensory patterns that take longer to learn, but can then express very fast behavioral responses (e.g. a “low” route; LeDoux, 1996). The OFC, on the other hand, may provide a more flexible method of stimulus-reward association that can learn more quickly, but that takes longer to generate behavioral responses (e.g. a “high” route).

However, this account of stimulus-reward associations leaves a number of important aspects of behavior unexplained. First and foremost is that novel experiences with non-primary rewards can be experienced as pleasurable. Humans in particular get pleasure from highly complex stimuli such as music, artwork, ideas, and photographs of natural scenes, including ones that have not been previously encountered. In addition, “aha” moments of "getting it" (comprehension) are pleasurable. In the absence of a primary or secondary reinforcer, it is unclear how either classical conditioning or reinforcement learning could account for such moments of pleasure. It is also not clear to what degree stimulus-reward associations could explain why sensory monotony and boredom is experienced as stressful and aversive, why taking a walk in a park is relaxing, or why humans express curiosity, being motivated to seek out new experiences and information.

2.3.2.1 Thirst for Knowledge: Curiosity and the Infovore. In addition to biological drive states that motivate feeding, reproductive and defensive behavior, (Biederman & Vessel, 2006) propose that humans have a drive to seek out and acquire information – humans are "infovores." Like other drive states, information foraging is accompanied by a need state (wanting), consumption is accompanied by pleasure (liking), and the pleasure from consumption acts as a reward signal to motivate memory for sources of information and reinforcement of the actions that led to the pleasing outcome. Yet in a way that is more pronounced than for other drive states, the outcomes that are experienced as pleasing change over time – being exposed to the same bit of information (e.g. comprehension of a theory, hearing a punchline, seeing a movie) is typically not as pleasurable a second time around. This "hedonic adaptation" means that humans are constantly seeking novel information (see below).

According to this theory, novelty alone is not sufficient to explain the pleasure derived from obtaining a novel bit of information, which is proportional to its informational complexity. An objectively novel pattern of noise does not contain interpretable features that engage human perceptual mechanisms, and a novel view of a familiar scene does not have as much capacity for pleasure as a new scene. On the other hand, the pleasure derived from a simple drawing can be drastically altered by the interpretation paired with the drawing. The pleasure derived from a sensory experience, then, is a function of the observers' past experience and their ability to parse the components of the experience - experiences that are both novel and richly interpretable are experienced as pleasurable. When viewing natural scene, for example, the pleasure derived is the result of processing that takes place at multiple levels of visual analysis, from a low level analysis of edges and local contrast, a mid-level extraction of surface and depth, and a higher-level recognition of shape, scene layout, and associations with meaning and past associations. (Biederman & Vessel, 2006) suggest that these latter stages of analysis play a stronger role in the pleasure derived from the experience than do the early stages.

A potential implementation of this principle may be found in the latter stages of the ventral visual pathway. The associative regions of the anterior temporal lobe, adjacent to the hippocampus, are known to represent aspects of objects and scene contexts (Staresina, Duncan, & Davachi, 2011), and respond to novel objects (Desimone, Erickson, & Miller, 1996; Henson, Cansino, Herron, Robb, & Rugg, 2003; Montaldi, Spencer, Roberts, & Mayes, 2006) and combinations of objects and contexts (Staresina et al., 2011; Suzuki & Naya, 2014). There are neural pathways that connect these regions to the hippocampus and amygdala, as well as to the striatum and orbitofrontal cortex (Hetherington et al., 2000; Rolls, 1999), providing several potential pathways by which such associative activity could lead to pleasure. Although the exact nature of these connections is not well understood, (Biederman & Vessel, 2006) suggest that the connections respect the hierarchical nature of sensory pathways: higher-level regions have stronger connections, and therefore greater influence, on the moment-to-moment pleasure we receive from sensory stimulation and learning about rewards.

Interestingly, it has been shown in macaque monkeys (Lewis et al., 1981) and in humans (Quirion & Pilapil, 1991) that there is a gradient of μ-opioid receptors in the ventral visual pathway, with concentrations being highest in the anterior regions adjacent to the hippocampal formation and amygdala. There is some evidence of a similar gradient in auditory and tactile pathways as well (Lewis et al., 1981). Although it is unknown if these receptors bind endogenous opioids that are released as a result of local activity or of activity at a distal site (such as the ventral striatum or amygdala), the known involvement of endogenous opioids in core liking (Berridge et al., 2009) is consistent with a graded involvement of regions of the ventral visual pathway in the hedonic consequences of visual perception.

Evidence for the existence of an "infovore" system has come from several lines of research. First, it is known that highly complex patterns of sensory experience with no immediate survival value such as music, paintings, abstract visual patterns, etc. can activate classical "reward" circuitry (e.g. the ventral striatum; Jacobsen, Schubotz, Hofel, & Von Cramon, 2006; Lewis et al., 1981; Salimpoor, Benovoy, Larcher, Dagher, & Zatorre, 2011; Vessel, Starr, & Rubin, 2012; Zatorre & Salimpoor, 2013), as can novel faces and scenes, which, although more directly linked to survival value, are also highly complex stimuli that can lead to pleasure in the absence of specific reinforcement histories (H. Kim, Adolphs, O'Doherty, & Shimojo, 2007; Yue, Vessel, & Biederman, 2007). Additionally, a study of preferences for good (t-shirts) found that regions of the ventral visual pathway show activity that is correlated with preferences for specific aspects of the stimuli, such as semantic preferences or visual aesthetic preferences, while activity in medial prefrontal cortex reflected the combined effects of both (Lim, O'Doherty, & Rangel, 2013). A study of humor found activation in the temporal poles, temporo-parietal junction, and in dorsal medial prefrontal cortex for combinations of visual cartoons with humorous interpretations when compared to non-humorous insight (Amir, Biederman, Wang, & Xu, 2013).

There is even some initial support for involvement of opioids in visual preferences. A recent paper investigating facial attractiveness found that both preference ratings (e.g. "liking") and amount of work performed to view a very attractive face ("wanting") were increased by administration of an opioid agonist (morphine) and decreased by an administration of an opioid antagonist (naloxone; Chelnokova et al., 2014).

In the following sections, we will review evidence that positive affective responses to sensory experiences are strongly influenced by their novelty and by the degree to which the experience allows for rich interpretation.

2.3.2.2 Effects of Repeated Exposure: Novelty and Familiarity Preferences. There are a number of lines of evidence that repeated presentation to a stimulus can lead to changes in pleasure and expressed preference. However, some lines of evidence point to a preference for familiar stimuli, while other lines of evidence suggest a preference for novel stimuli.

In 1968 Robert Zajonc reported that nonsense words that were shown to an observer were subsequently preferred over other, novel nonsense words that the observer had not seen, and proposed that "mere exposure" to a stimulus can increase liking (Zajonc, 1968). He claimed that this example was evidence that "feelings need no inferences" (Zajonc, 1980), by which he meant that emotional responses could occur in the absence of cognition, and even in the absence of awareness. Subsequent research has shown that "subliminal" exposure durations that are too brief for conscious perception and subsequent recognition can still lead to greater than chance affective discrimination, with previously exposed images being preferred (Seamon & Kenrick, 1993). However, a review and meta-analysis of the mere-exposure literature revealed a number of failures to replicate this result, and extreme sensitivity to many factors, such as the number of stimuli used in an experiment, stimulus brightness and contrast, participant mood, etc., as well as a susceptibility to being outweighed by boredom (Bornstein, 1989).

A second line of research has highlighted the opposite effect – a preference for novel stimuli. (Berlyne, 1970) presented evidence that ratings of both preference and of interest for paintings and other images declined over repeated presentations. Preferences for real-world scenes also show declines over repeated exposures, regardless of whether the scene was initially a highly preferred scene or a low-preferred scene (Biederman & Vessel, 2006; Vessel & Biederman, 2002).

A related set of phenomenon is broadly referred to as "hedonic adaptation" – e.g. a reduced affective response (positive or negative) upon continued or repeated exposure to the same stimulus or event. Reduced hedonic responding can occur either because of reduced sensory sensitivity to a stimulus, or due to a change in the relationship between stimulation level and hedonic response, such as a shift in adaptation levels or desensitization (Frederick & Loewenstein, 1999). Such changes serve to protect an organism from consistent negative stimuli and to maximize the sensitivity of perceptual mechanisms to changing levels of stimulation in the environment. Theoretical models of hedonic adaptation typically suggest that the adaptation level, e.g. the level of a stimulus that elicits no response, is a weighted average of past stimulus levels, with more recent events being weighted more strongly (Frederick & Loewenstein, 1999). The affective intensity of a constant stimulus would therefore diminish over time. A related effect is what

(Kahneman, 1999) refers to as the "satisfaction treadmill" - as the intensity and frequency of hedonically positive events increases in one's environment, increasingly intense events are required to achieve the same level of satisfaction. Interestingly, it is known that some stimuli, such as noises, do *not* show such adaptation, and can even produce sensitization (Frederick & Loewenstein, 1999).

Several aspects of hedonic adaptation are particularly relevant for LDSM. Repetitive exposure to the same environment and stimuli (e.g. media) are likely to reduce hedonic responding to those stimuli. However, an astronaut may also show an advantageous adaptation to the reduced sensory environment – there is evidence that some prisoners in solitary confinement exhibit *less* boredom over the course of their sentence (Deaton, Berg, Richlin, & Litrownick, 1977; Suedfeld, Ramirez, Deaton, & Baker-Brown, 1982). Anticipation of future stimulation levels can influence adaptation (potentially related to the "third quarter" phenomenon) and the timing of repeated stimulation is critical – the same stimulus can show different degrees of adaptation, and even increases in responding, depending on the time interval between repetitions (Frederick & Loewenstein, 1999). Finally, uncertainty impedes adaptation – the introduction of variability and uncertainty in the repetition of a stimulus reduces its predictability and adaptation.

This has potential implications for the design of an optimal schedule for delivery of positive hedonic experiences during LDSM – on the one hand, it is important that there be assurances of the receipt of regular information delivery and communication, as a sudden drop-off or missed delivery could be perceived as an especially negative event. On the other hand, the delivery of additional experiences in an *unscheduled* manner (e.g. surprise deliveries or "Easter eggs") may be a cost-effective way of enhancing their positive hedonic impact. Future work on the use of sensory countermeasures should investigate a) the degree of hedonic adaptation experienced for different sensory experiences (e.g. visual, auditory, food, informational, etc.), as well as the effect of delivery schedule (period, regularity) on adaptation.

Recent work by Shimojo and his colleagues suggest that the relationship between exposure and preference may be quite complicated. When asked to indicate preference choices between a novel image and an image that was repeated on each trial, observers developed a preference for familiar faces over novel faces, yet developed a preference for novel scenes over repeated scenes (and no difference for geometrical figures; J. Park, Shimojo, & Shimojo, 2010) - repeated exposure can have different effects for different stimulus categories. A subsequent study found that the preference for novel scenes became non-significant when observers passively viewed the pairs of images rather than making a preference judgment, and that asking observers to make a different "objective" judgment (warm versus cool color temperature) reinstated the novelty preference for scenes (Liao, Yeh, & Shimojo, 2011). These results suggest that novelty preferences for scenes depend on depth of processing – greater scrutiny and engagement with a scene leads to faster development of novelty preferences. Why faces and scenes show such different patterns is unclear. One potential explanation is that the divergent effects of repetition are due to differences in how these two stimulus categories are encoded (e.g. reliance on a "distributed" code of small differences across many features for faces versus reliance on a "sparse" code of large differences on a smaller subset of features for scenes). Alternatively, it is possible that differences in gaze patterns or response contingencies for faces versus scenes may drive the divergent effects of repeated exposure.

Work on links between behavioral "priming" and neural repetition suppression hint at a potential reconciliation of these disparate observations. Observers are typically unable to recognize images of objects that are presented for shorter than 60 milliseconds (Bar & Biederman, 1998). However, subsequent presentations at the same brief duration allow for increasing recognition rates, a phenomenon referred to as "subliminal visual priming" (Bar & Biederman, 1998). Theoretical accounts for priming suggest that the first exposure activates neural circuits that represent features of the visual stimulus at a subthreshold level that is not sufficient for the activation of neurons representing the identity of the object, and that subsequent exposures reactivate the same neural circuits, requiring less activation to cross firing thresholds and activate conscious recognition (Bar & Biederman, 1998). Brain imaging experiments suggest that visual priming may be related to repetition suppression, which is the finding that repeated stimulation of the same neural circuit typically leads to decreasing response magnitudes over repetitions (Desimone et al., 1996; Sayres & Grill-Spector, 2008). When considered within the context of the hierarchical structure of the ventral visual pathway, this suggests that repeated exposures to a novel image allow for the propagation of signals further along the pathway by "priming" lower-level features at each stage. After activation of higher-level representations of object features and identity, these regions then also show decreases in firing with continued exposure. If activation in higher-level regions of sensory hierarchies are more tightly linked to affective responses, then one would predict an inverted U-shaped curve relating exposure to preference – as an observer is in the process of attempting to understand what they are looking at, activation in sensory hierarchies will progressively move higher, resulting in more pleasure to previously exposed stimuli. However, once recognition has occurred (the "aha" moment of "getting it"), then subsequent presentations lead to less activation at all levels of the hierarchy due to repetition suppression, and hence less pleasure.

This explanation shares some similarity with "processing fluency" accounts of preference, which claim that events that are "easier" to process lead to more pleasure (Reber, Schwarz, & Winkielman, 2004). A number of features that increase processing fluency and have been shown to be correlated with pleasure (contrast, symmetry; Reber et al., 2004), and manipulations of fluency have been shown to be correlated with facial EMG measures of pleasure (Winkielman & Cacioppo, 2001). Activity in the perirhinal cortex, a region in the medial temporal lobe that sits at the nexus between the ventral visual pathway and medial temporal lobe memory systems, shows activation that is sensitive to fluency manipulations (Dew & Cabeza, 2013). However, although processing fluency, on its own, may be related to the pleasure obtained from understanding, it cannot account for the subsequent reductions in pleasure with repeated exposure for an experience that has been cognitively mastered in its entirety.

2.3.2.3 Importance of Semantic Associations (Meaning). The positive effects of sensory experiences are also strongly influenced by the meaning that is associated with an experience, as well as perceived personal relevance.

A central debate in experimental aesthetics is the relative role of objective, low-level features for preference formation versus internal, subjective factors, such as the semantic meanings attributed to an experience. A number of studies have claimed to show that preferences for real-world scenes and objects are influenced by a number of low- and mid-level features, such as the presence of symmetry (Rentschler, Jüttner, Unzicker, & Landis, 1999), aspect ratio (McManus, 1980), contrast and sharpness (Reber et al., 2004; Tinio, Leder, & Strasser, 2011), specific colors (McManus, Jones, & Cottrell, 1981), straight vs. curved lines (Bar & Neta, 2006) and fractal geometry/self-similarity (Aks & Sprott, 1996; D. J. Graham & Field, 2007). However, other authors have emphasized the importance of internal, subjective factors that are not tied to any objective stimulus features that can be extracted in the absence of knowledge about the perceiver's previous experiences. Examples of such subjective factors include novelty (Berlyne, 1970), associative meaning (Martindale, 1984), "processing fluency" (Reber et al., 2004) and emotional responses (Palmer, Schloss, Xu, & Prado-Leon, 2013; Silvia, 2005).

By measuring the degree to which different people share similar preferences, Vessel and Rubin (2010) were able to disentangle the relative role of low-level, objective features of images versus higher-level subjective determinants (such as semantic associations) in determining aesthetic preferences. They found that observers showed a high degree of agreement for which real-world scenes they preferred, but markedly lower agreement for which abstract images they preferred. Since the abstract images contained variation in objective, low-level features such as color, shape, contrast, and the presence of surfaces, these features cannot be the primary determinant of preferences in the real-world scenes, or the level of agreement would have been similar for the two categories. The higher agreement for the real-world scenes was therefore a product of the meanings that people associated with the scenes – when the interpretation of an image is similar across a group of people, then it is likely that preferences for that image will also be similar across people (Vessel & Rubin, 2010). A similar conclusion was reached in a study on color preferences across a variety of cultures. Palmer and Schloss (2010) found that although there is a strong degree of coherence across people in their preferences for a range of colors, individual color preferences are best predicted by the valence attributed to objects that people associate with each color. Several studies using visual artwork as stimuli corroborate the importance of meaning on aesthetic appreciation (Millis, 2001; Russell, 2003).

It is important to note that these findings do not suggest that low-level objective features are irrelevant for determining the nature and quality of aesthetic preferences. However, the effect of objective stimulus features on an aesthetic experience is largely mediated by internal, subjective factors, and, when present, differences in higher-level meaning will have a larger effect on aesthetic appreciation than low-level features.

2.3.3 Sensory Stimulation and Positive Emotional States. Emotions can be characterized as responses to significant events that involve one or more components of subjective experience, behavior, and physiological reactions (Fridja, 1999). Affective states such as hedonic liking, incentive salience, threat and loss form the core components of emotional responses to events. A defining condition of emotional states, however, is that they elicit a change in the control of behavior or thought, a property referred to as "control precedence" (Fridja, 1999). Note that although emotional responses often also have corresponding physiological correlates (e.g. increased arousal) and facial expressions (e.g. smiling, frowning), this is not always the case.

Although there is much that is not understood about the anatomical substrates of emotional processes, the amygdala, the OFC, and their output pathways form a basic core for representing associations with reinforcers and subsequently influencing behavior. The primary pathways by which the amygdala, hippocampus and OFC can directly influence behavior are through connections to the ventral striatum (including the nucleus accumbens) and the hypothalamus. Autonomic and endocrine aspects of emotional response are mediated via outputs to the hypothalamus (LeDoux, Iwata, Cicchetti, & Reis, 1988; Rolls, 1999; Swanson, 2000). The ventral striatum, which in monkeys shows responses to novel visual stimuli, reinforced stimuli and aversive stimuli is part of a primary output pathway for implicit emotional responses that includes a striatal-pallidal-thalamo-cortical loop (Rolls, 1999). Explicit, conscious behavioral responses are mediated via cortical systems (Berridge & Kringelbach, 2013; Rolls, 1999).

Below we will outline a few basic frameworks for understanding emotional response and their relevance for sensory stimulation augmentation.

2.3.3.1 Frameworks for Understanding Emotion. Dimensional theories of emotion place different emotions as points along continuous dimensions of underlying importance, such as valence. For example, the 2-factor theory of Bradley, Greenwald, Petry, and Lang (1992) highlights the difference between emotional states in terms of affective valence (positive to negative) and degree of arousal. This theory captures salient differences in physiological response and approach/avoidance behaviors for different stimuli, and may be a good description of subcortical aspects of emotion. However, it is likely overly simplistic (e.g. high arousal, negative valence stimuli can be either fearful or disgusting;

positive valence stimuli such as erotica and cute animals are very different), and it does not capture the fact that valence may not always be bidirectional, but can in fact be two separate dimensions.

A related theory is that emotions are states elicited by rewards and punishments, as well as their omission or termination (Rolls, 1999). In this framework, positive emotions like pleasure and elation are associated with the presentation of positive reinforcers, negative emotions like fear and terror are associated with negative reinforcers, relief is associated with the omission or termination of a negative reinforcer, and frustration and anger are associated with the omission or termination of a positive reinforcer. Although more nuanced than a single valence axis, this theory suffers from some of the same issues as the valence/arousal framework, in that it fails to make clear predictions for how states such as sadness and anger differ in their behavioral outcomes.

Another prominent view of emotion is that there are discrete systems that mediate a small and distinct set of basic emotions: often happiness, sadness, anger, fear, disgust, and sometimes surprise, curiosity, interest, contempt, love, shame/guilt (Ekman, 1992; Izard, 1977). This view is partly derived from the common experience that the conscious experience of emotional states often has the quality of feeling "irreducible" to simpler elements (e.g. Izard, 1977; Johnson-Laird & Oatley, 1989). A correspondence of emotions is often made with a set of distinct facial expressions that are claimed to be universal across different cultures (Etcoff & Magee, 1992; Susskind et al., 2008; Webster, Kaping, Mizokami, & Duhamel, 2004) though such claims have been disputed (Gendron, Roberson, van der Vyver, & Barrett, 2014; Jack, Garrod, Yu, Caldara, & Schyns, 2012). For example, recent work on has shown that spontaneous facial expressions produced during moments of extreme emotion with *opposite* valence (e.g. pleasure versus pain, anguish versus exaltation) are easily confused when body cues are removed (Aviezer, Trope, & Todorov, 2012).

Within these frameworks, an emotion like "joy" or happiness (though this may better correspond to a mood state) is relatively well defined as an emotional state brought about by the presence of a positive reinforcer. However, the status of states such as curiosity and interest are less well defined, and no distinction is made between emotional states that are brought about by conditioned reinforcers versus through information foraging.

Appraisal theories, on the other hand, characterize emotions as a set of appraisals of person-event interactions, and suggest that emotional responses are not entirely separate from cognitive processes (Ellsworth & Scherer, 2003; Lazarus, 1991). Appraisal theory captures important aspects of emotional responses that are relevant for sensory stimulation. Emotions result from ongoing appraisals, and the appraisals need not be conscious. Some of the central appraisals include novelty, pleasantness, goal significance (importance), certainty, agency (cause), coping ability and compatibility with standards (Ellsworth & Scherer, 2003). This framework is useful for understanding coping and resiliency – for example, novelty is experienced as positive when coupled with ability to cope, but negative when coping potential is low. Additionally, appraisal theory is well suited to explain aspects of curiosity, interest and other emotional states that are related to knowledge acquisition (Silvia, 2008).

2.3.3.2 Knowledge-Based Emotions. Information foraging behavior is linked to a set of emotional states that may be referred to as “knowledge-based” emotions. Like other emotions, interest, confusion, surprise and awe involve physiological changes, have characteristic vocal and facial expressions, involve cognitive appraisals, have corresponding subjective feelings, and play an adaptive role in survival (Keltner & Shiota, 2003; Silvia, 2008). Similar to Biederman and Vessel (2006) proposal, Silvia suggests that interest arises from an appraisal of novelty-complexity and coping-potential (or comprehensibility) - events that are new and comprehensible will be interesting (Turner & Silvia, 2006). Confusion, however, results when there is a low ability to understand. These emotions are “knowledge based” or “epistemological” in that they are related to the acquisition of information or knowledge: they are caused by people’s beliefs about their own knowledge, and stem from goals related to learning (Keltner & Shiota, 2003; Silvia, 2010). Note that frustration, which can occur in the context of a variety of drive states, results when there is a lack of agency for achieving one’s goals.

Research on surprise has focused on a similar set of processes. Current theoretical models posit that surprise results when an event occurs in the environment that is out of line with one’s expectations, and that it involves a “noticing” stage of unexpectedness or comparison with likely outcomes, and an “understanding” stage during which one’s model of the environment is updated or modified to incorporate the new information (Munnich, Ranney, & Song, 2007).

Aesthetic experiences, such as interactions with visual artwork or music (and perhaps even with sunsets or mathematical theories), share strong similarities with such emotional states. Aesthetic emotions, such as beauty, awe, wonder and the sublime, may represent a subclass of knowledge-based emotions. In an fMRI brain imaging experiment in which observers were shown visual artworks and asked to indicate which works they found to be aesthetically “moving,” two separate networks were found to reflect the observers’ aesthetic reactions (Vessel et al., 2012). The first was a network of posterior regions, likely at the anterior end of the ventral visual pathway, showed a linear correlation with increasing aesthetic appeal. A second network, composed primarily of frontal regions (including the lateral OFC and inferior frontal gyrus *pars triangularis*), was not differentially activated by most paintings, including those that were not liked and those that were mildly liked - this network only showed an increased response for the images an observer found *most* moving (Vessel et al., 2012). The authors hypothesized that the first network reflected activation of a stimulus-driven (feedforward) mechanism linking a perceptual and semantic analysis with pleasure and liking, whereas the second network reflected an "aesthetic" response that integrates over a variety of emotional systems (or appraisals).

In addition to the frontal regions that were activated above baseline only for the most moving images, (Vessel et al., 2012) also found selective responses for only the most moving trials in central nodes of the "default-mode" network (DMN). The DMN comprises a set of regions that are normally suppressed when an individual engages with an externally-directed task or stimulus - tasks requiring an observer to look at images, respond to cues, make motor movements, etc. are all correlated with decreased BOLD signal in the DMN regions when compared to a "resting" baseline during which the observer has no explicit task (Shulman et al., 1997; Simpson, Drevets, Snyder, Gusnard, & Raichle, 2001). Subsequent work has highlighted the role that the DMN plays in social cognition (e.g. self vs. other and theory of mind), autobiographical memory and prospective planning (Amodio & Frith, 2006; Andrews-Hanna, Reidler, Sepulcre, Poulin, & Buckner, 2010; Buckner, Andrews-Hanna, & Schacter, 2008; Mitchell, Macrae, & Banaji, 2006; Ochsner et al., 2005; Ochsner et al., 2004; Whitfield-Gabrieli et al., 2011). This has led to a convergent view of the DMN as a network of regions that are concerned with aspects of self-referential and self-relevant mentation (Andrews-Hanna et al., 2010; Kelley et al., 2002; Northoff et al., 2006; Spreng, Mar, & Kim, 2009).

The engagement of internally focused, self-relevant mentation is likely a key characteristic that distinguishes aesthetic appreciation from pleasure. The anterior medial prefrontal cortex, along with other core regions of the DMN, are suppressed when an individual looks at and responds to images, including most images of artwork. However, when an individual looks at an artwork that is subsequently rated as highly moving, there is a release from suppression in the DMN, and its activation rises to a level at or above that seen during the intertrial interval. Note that unlike DMN activity during "rest" periods when an observer's attention and thoughts are solely inwardly focused, the increase in the DMN when viewing highly moving images is coincident with activation in regions of the ventral visual pathway.

This coactivation of the DMN and sensory regions, which appears to be extremely rare, likely reflects the importance of self-relevance for aesthetically moving experiences, and may indeed be a hallmark of aesthetic experience (Vessel, Starr, & Rubin, 2013). Intense aesthetic experiences, and other, similar emotional experiences (e.g. inspiration, "aha" moments), likely represent moments during which the external world comes to affect "the self" and one's relationship to the world.

With respect to spaceflight and long-duration missions, it is clear that curiosity, awe, and moments of inspiration are vital to well-being. The positive emotional (salutogenic) benefits of exploration that have been reported by adventurers in remote and dangerous environments may be at least partly explained by similar moments of resonance between the DMN and externally directed networks during "peak" experiences and moments of discovery and meaningful engagement. Similarly, a lack of engagement of knowledge-based emotions, including an inability to satiate the information foraging drive, is likely to result in boredom, frustration and stress.

2.3.3.3 Implications for Sensory Stimulation Augmentation. There are several aspects of emotion research that are relevant for evaluating the effectiveness of potential countermeasures for reduced sensory stimulation and monotony. It is clear that emotional responses are not necessarily the "enemy" of performance – although it is well documented that decision making and performance can be negatively impacted by arousal and threat (Eysenck, Derakshan, Santos, & Calvo, 2007; Lapate et al., 2014; Schmader & Johns, 2003), it is also the case that the experience of *positive* emotional states can be beneficial to long-term cognitive functioning and mood. Positive emotional responses can lead to changes in control state, adding to a person's appraisal of coping ability and control (Folkman & Moskowitz, 2000; S. L. Gable, Reis, Impett, & Asher, 2004; S. H. Kim & Hamann, 2007). Although sensory experiences can be affectively valenced without being "emotional" per se, the positive effects of sensory stimulation on mood may require such changes in control. Further research will be needed to better clarify whether sensory experiences must rise above simple affective states (sensory pleasure) to emotional states in order to have a beneficial effect on well-being.

2.3.4 How Sensory Stimulation Affects Stress and Coping. A major goal of BHP's mission is to understand the factors that contribute to an astronaut's "resilience," which can be defined as the ability to perform mission critical operations while under stress, and to recover from stressful situations without lasting deficits in performance. In order to evaluate the effectiveness of countermeasures targeting the augmentation of sensory stimulation, it is therefore of critical importance to understand the relationship between sensory stimulation and stress.

For the purpose of this review, we will define stress as a set of physiological responses to a perceived disturbance in "allostasis", including threats to one's safety and drive states such as hunger or thirst (Sapolsky, 1999). Psychological stress relates to one's ability to cope with a challenge (R. Kaplan & Kaplan, 1995), and typically goes together with physical stress. At its core, the stress response involves the activation of paraventricular nucleus of the hypothalamus, which stimulates the anterior pituitary to release adrenocorticotropic hormone (ACTH) into the bloodstream, which in turn signals the cortex of the adrenal gland to release cortisol into the bloodstream (the "HPA" axis). The coordinated action of these neural and hormonal systems prepare the body for a period of exertion by essentially turning off any "housekeeping" functions and putting the body and brain in a state of heightened alertness and action readiness. Output from the central nucleus of the amygdala, such as in response to a perceived threat, upregulates the HPA axis (Herman & Cullinan, 1997; Tsigos & Chrousos, 2002). The hippocampus, which contains glucocorticoid receptors and is therefore sensitive to HPA activation, downregulates hypothalamic function, providing one pathway for reducing the stress response.

Despite the obvious benefits to an organism's survival of having such an "emergency mode" at its disposal, the stress response is not always adaptive, particularly when the body is not given sufficient time to recover from the negative side effects of stress. Humans, in particular, are capable of cognitively triggering the stress response to perceived stressors that are not immediate and are of an uncertain likelihood. During spaceflight, particularly LSDM missions, the frequency of real and perceived threats to safety can easily rise to a level that may put an astronaut in danger of being in a state of chronically elevated stress, which is well-documented to have negative health consequences for both the body and the brain (Sapolsky, 1999).

There are at least three ways in which sensory stimulation interacts with stress. First, certain forms of sensory stimulation may act as a stressor. Second, a *lack* of sensory stimulation may also act as a stressor. Finally, certain forms of sensory stimulation can function as *coping mechanisms*, allowing an individual to better deal with other (real or perceived) stressors in their environment. In this review, we will focus primarily on how reduced sensory stimulation can act as a stressor as well as on ways that sensory stimulation augmentation can help cope with stress; the role of sensory stimulation as a stressor will be addressed only briefly at the end of this section.

2.3.4.1 Activation of the Stress Response by Chronically Low Sensory Stimulation and Sensory Monotony. As detailed above, humans have a drive to seek out novel but interpretable information, and get pleasure from doing so. An environment lacking in sensory stimulation leads to understimulation of this seeking drive, which is experienced as boredom and frustration. Boredom can be a chronic and pervasive stressor, and is associated with mental health symptoms, impulse control deficits, workplace errors, and increased mortality (Eastwood, Frischen, Fenske, & Smilek, 2012; Mann & Robinson, 2009). Within military situations, a form of "existential boredom" has been found to occur when soldiers believe that their efforts and sacrifices are unimportant and unappreciated, and can lead to stress (Bartone, 2005). Monotony and understimulation also constrain a person's ability to adapt to an environment, which affects how people evaluate their surroundings and their ability to cope (e.g. situational meaning; De La Torre et al., 2012; Paulus et al., 2009). There is some evidence that certain personality types (sensation seeking) may be more susceptible to boredom during monotonous conditions (e.g. Thiffault & Bergeron, 2003).

Although very little is understood about the mechanisms by which understimulation, monotony and boredom lead to stress, two brain systems that are of central importance are those that mediate the maintenance of drive states and exploratory behaviors, and those that regulate aspects of attention. Prudkov (2013) suggests that conflict between novelty-processing mechanisms and the monotony of long-term activities can result in mental effort and fatigue, and there are a number of studies that link boredom to attentional systems for orienting, executive control and alerting (Eastwood et al., 2012). Below, we will provide an outline of the neural systems controlling other drive states such as hunger or thirst, and how their disregulation can lead to stress, and will also suggest some potential links to attention.

The stress response is one of the many coordinated behavioral states regulated by the hypothalamus. A series of nuclei in the hypothalamus and brainstem, referred to by Swanson (2000) as the behavioral control column (BCC), act as controllers for behaviors key to survival, such as eating, drinking, reproductive behaviors, defensive behaviors, and foraging behaviors. These nuclei are critical for establishing the goals of motivated behavior, maintaining "set points" for various drives and coordinating behavioral responses when a deviation from allostasis is present. The heavily interconnected nature of the hypothalamus provides a substrate by which imbalances in any part of the BCC can lead to a stress response.

Importantly, the caudal portion of the BCC, which includes the ventral tegmental area (VTA), substantia nigra pars reticulata (SNr) and mammillary bodies, are of central importance for controlling locomotor behavior, orienting reactions, and head direction. These regions are also key sources of dopamine, and are implicated in responding to reward (Schultz et al., 1998). Together, the caudal BCC coordinates action during all 3 phases of motivated behaviors (initiation, procurement and consummation), regardless of the drive state being satisfied (Swanson, 2000). Information about the sensory environment important for reflex behaviors, as well as cognitive information relevant for the voluntary control of behavior and information about an organism's behavioral "state" (such as degree of arousal) all reach the BCC through a "triple descending" set of projections from various regions of the cortex that project first to regions of the striatum and then to regions of the pallidum (Swanson, 2000). The combination of these three projections onto the BCC provides excitatory input (cortex), inhibitory input (striatum), and "disinhibitory" input (inhibition of inhibition; pallidum).

Within this scheme, there are several circuits that are relevant for information foraging and the link between sensory stimulation and stress. First, large regions of the cortex (including sensory cortices, association cortices and the orbitofrontal cortex) affect the SNr through a triple-descending projection that involves the dorsal striatum and globus pallidus. Second, a more narrow set of regions, including the entorhinal and perirhinal regions of hippocampal cortex, medial prefrontal cortex and insular cortex, affect the VTA through the ventral striatum (nucleus accumbens) and ventral pallidum. As mentioned above, these regions appear to be key regions for mediating "wanting" and "liking" responses (Berridge & Kringelbach, 2013).

The thirst for knowledge can trigger a state of curiosity, which shares features in common with a drive state (e.g. Loewenstein, 1994), and may therefore rely on portions of the BCC for its maintenance (note, however, that Loewenstein claims that people will willingly enter into activities that trigger curiosity, unlike other drive states). Satisfaction of this state comes in the form of filling a gap in understanding. This state can be brought about as a "reflex" to a sensory event (e.g. a loud noise), voluntarily through cognitive thought ("I wonder"), and through boredom. The BCC is likely involved in maintaining a "set point" of basal drive that represents an optimal level of information intake and which, under most circumstances, is easily met by one's physical and mental environment. Activation of the exploratory (caudal) segment of the BCC leads to the acquisition of information (in conjunction with executive and attentional systems), which leads to "consummatory" activation in the ventral striatum and ventral pallidum, and a downregulation of the BCC drive state (hence "closing the loop"). However, under conditions of reduced sensory stimulation and monotony, these unmet goal states lead to chronic activation of the BCC. This chronic activation of the BCC's centers for goal state maintenance and control of foraging may be experienced as stress, and activate the HPA axis.

This story is clearly highly incomplete and rests on many unknowns. For example, it is unclear how such a drive state would be instantiated in the BCC. One possibility is that the rostral (goal) part of the BCC in humans has been adapted to represent this abstract drive. A second possibility is that there is a special adaptation of the caudal (locomotor) BCC that works in concert with cortical regions involved in monitoring and goal directed behavior to support information foraging. It is also unclear what mechanisms allow external or internal events to lead to the instantiation of this drive.

The role of the amygdala in this system is unclear – although the amygdala is known to have a role in representing associations of stimuli with positive or negative reinforcers (Paton et al., 2006) and its activation by threatening stimuli has been shown to activate the HPA axis, it is unclear whether it plays a role in the stressful consequences of understimulation of an information seeking drive, as is experienced during chronic boredom and monotony.

The hippocampus, on the other hand, which is known to play a regulatory role in the stress response (Herman & Cullinan, 1997; Tsigos & Chrousos, 2002), quite likely also plays a key role in signaling the satiation of a curiosity drive state. The consumption of novel, interpretable information leads to an increase in associative activity in cortical regions of the medial temporal lobe, which then affect ongoing activity in the hippocampal formation. Hippocampal activation affects the BCC via the septum (Swanson, 2000), and has been shown to suppress HPA axis function.

Regions of the prefrontal cortex, particularly the dorsolateral prefrontal cortex (dlPFC) and anterior cingulate cortex (ACC), are linked to cognitive control mechanisms that oversee the execution of goal directed behaviors, such as performance monitoring and deployment of directed attention. In the absence of exogenous stimulation that engages attention and can satisfy an information foraging drive state, effort must be expended to deploy directed attention. As will be further discussed below, mental fatigue may, in some cases, be a consequence of a lack of attentional resources (e.g. directed attention), which can be a cause of stress. Understanding this complicated relationship between stress and attention will be very important for the design of countermeasures that restore attentional capacities and/or reduce stress – indeed, it is likely that countermeasures that address one are likely to be related to the other.

2.3.4.2 Restorative Properties of Sensory Stimulation: Exposure to Natural Environments In addition to the role that sensory stimulation plays in satisfying active information seeking (and avoidance of the stressful consequences of an unmet curiosity drive state), certain forms of sensory stimulation also have restorative properties and can aid an individual in coping with stressors. Coping refers to the ability of an individual to reduce a stressor, either by changing one's environment, reducing one's exposure to the stressor, or managing the effects of the stressor (e.g. adapting, reappraisal). Control is a key aspect of stress and coping: situations of low or no control over environmental stressors can lead to anxiety.

There is evidence that "access to nature" has an effect on health. Research going back to the 1980's has shown that having a view of natural elements has beneficial health effects in a variety of settings, including hospitals, prisons and the workplace. In an influential 1984 paper in Science, Roger Ulrich reported that recovery time for patients who had undergone gall bladder surgery was affected by the view out their hospital room window. Patients who had a view of trees with foliage, as opposed to those with a view of a brick wall, had fewer days of postoperative hospitalization and required significantly lower doses of analgesic medication on days 2 through 5 of their post-surgery recovery (Ulrich, 1984). There was also a trend for these patients to have fewer minor complications and fewer nurse reports of negative affect. A 1981 paper on health care service in prisons found that inmates placed in cells with a view outside the prison had 24% fewer sick calls and incidents of stress-related symptoms (e.g. headaches) than inmates in cells with no exterior view (Moore & Arch, 1981). Work by S. Kaplan (1995) highlighted the effects of having a view of natural elements (e.g. trees or flowers) on worker satisfaction. Individuals with views of natural elements reported lower stress and higher job satisfaction, as well as fewer illnesses and headaches (S. Kaplan, 1995). Subsequent studies have found that views of nature (trees, plans, vegetation, foliage) mitigated the negative effects of job stress on intention to quit (Leather, Pyrgas, Beale, & Lawrence, 1998), that exposure to sunlight significantly increased reported job satisfaction and well-being, and decreased intention to quit (Leather et al., 1998), and that nature contact in the workplace is associated with lower perceived stress and better general health (Largo-Wight, Chen, Dodd, & Weiler, 2011). Even the nature of people's aspirations, whether intrinsically directed (e.g. to earn money) versus extrinsically directed (e.g. to help people), appear to be affected by exposure to nature (Weinstein, Przybylski, & Ryan, 2009).

This body of evidence has led to the development of the concept of a "restorative environment" as one that aids in the recovery from stressors and mental fatigue (S. Kaplan, 1995; Ulrich, 1984). Subsequent work in the past two decades linking exposure to nature and stress has led to the development of several theoretical perspectives and an exploration of parameters that mediate the restorative effects.

There are two primary theories for how certain environments allow restoration and stress reduction. The first, exemplified by Ulrich's "psycho-evolutionary" theory (Ulrich, 1984), proposes that viewing natural environments leads directly to a change in affective state, thereby reducing stress. Ulrich claims that there is a fast, direct effect of natural environments on affect, emotion and mood (e.g. positive and negative valence systems), resulting in increased positive feelings (liking), decreased negative affect (e.g. fear and anger), suppression of stressful thoughts, increased parasympathetic tone, and sustained (non-vigilant) attention. He reports that observers who were shown a movie of a natural environment had better recovery from the effects of an acute stressor (watching a stress-inducing movie) than observers who were shown a movie of an urban environment (traffic, pedestrian mall), as indexed by facial EMG (frontalis, above eyes), skin conductance (SCR), changes in blood pressure and heard rate, and self-report of emotional states (Ulrich et al., 1991). Significant differences were seen within several minutes after onset of the restorative environment, supporting his claim that the effects of a natural environment on affect and physiological stress are immediate.

Several recent studies have extended these findings by investigating the effects of direct experience with natural settings on levels of salivary cortisol and other measures of physiological stress. Walking in the forest, compared to a city environment, was associated with lower salivary cortisol, lower pulse, lower blood pressure, greater parasympathetic tone, and less sympathetic tone (B. J. Park et al., 2007; J. Park et al., 2010). Thirty minutes of gardening following a stress inducer (Stroop task) led to greater decreases in salivary cortisol, and greater restoration of positive mood, than did thirty minutes of reading (Van Den Berg & Custers, 2011). The percentage of green space available in a resident's postal code was predictive of a steeper slope in diurnal cortisol levels even when controlling for individuals' level of physical activity (flatter cortisol levels are indicative of circadian rhythm dysregulation), and showed a negative relationship to self-reported stress levels (Thompson-Schill & Coutanche, 2012). Despite several reports that have failed to find beneficial effects of natural environments, these studies provide solid evidence linking acute and long-term exposure to natural environments with reductions in physiological and self-report measures of stress.

The second theory proposes that the positive, stress-reducing effects of experiencing natural environments are mediated by changes in one's ability to deploy voluntary attention. Attention can be separated into two component processes: involuntary attention involves the capture of attention in a bottom-up, stimulus driven fashion, whereas directed (voluntary) attention involves top-down guidance of attention by cognitive-control processes, such as task demands or conflict resolution (Fan, McCandliss, Sommer, Raz, & Posner, 2002; Jonides, 1981). Brain imaging studies have identified separable neural networks mediating these two forms of attention (Corbetta & Shulman, 2002). Attention restoration theory (ART) holds that prolonged efforts to maintain focused attention result in mental fatigue, and that interactions with nature allow for a recovery of directed attention abilities (R. Kaplan & Kaplan, 1989; S. Kaplan, 1995) that are crucial for effective cognitive functioning. Several features of directed attention are important for understanding the potential restorative effects of natural environments. Directed attention is under voluntary control, requires effort to employ, and involves inhibitory selection mechanisms that maintain focus by suppressing attention to competing targets (distractions). These aspects of directed attention make it particularly susceptible to fatigue.

According to ART, immersion in most natural environments mildly engages a form of involuntary attention that is easily maintained and not subject to fatigue, allowing directed attention mechanisms to rest and recover. A number of studies have found evidence to support the hypothesis that interactions with nature improve attention and memory, both in normal populations and in individuals in a variety of hospital care environments (see Berto, 2005; Cimprich, 1992, 1993; Ottosson & Grahn, 2005; Tennessen & Cimprich, 1995). For example, taking a walk in a natural environment, as opposed to an urban environment, improves performance on a backwards digit-span task measuring directed attention (Berman, Jonides, & Kaplan, 2008) and on a proofreading task (Hartig, Mang, & Evans, 1991). Even simply viewing images of natural scenes, as opposed to urban scenes, improves performance on a backwards-digit span task (Berman et al., 2008), as well as on a cognitively fatiguing sustained attentional task (Berto, 2005).

Within Kaplan's framework, the restorative properties of an environment depend on a number of factors. The primary factor is whether or not an environment engages a form of indirect attention that Kaplan refers to as "soft fascination." Gazing at clouds, sunsets, or water patterns mildly engage involuntary attention, feel effortless, and allow other thoughts to occur. On the other hand, environments that require direct, voluntary attention (such as monitoring for oncoming traffic when crossing the street) or that are attentionally "demanding" (e.g. an auto race, or a snake in the grass) are not restorative. While looking at high-fascination images, observers showed fewer fixations (Berto, Massaccesi, & Pasini, 2008), and responded more quickly to invalidly-cued targets in an attentional cueing task (Berto, Baroni, Zainaghi, & Bettella, 2010). In addition to fascination, Kaplan claims that restorative environments require physical or conceptual distance from the ordinary ("being away"), a large enough extent or scope to engage the mind (either through its size, complexity, or presence of objects that provide a connection to a larger context), and compatibility with a person's inclinations (e.g. presence of hiking trails, recreation opportunities, etc.). Several groups have developed questionnaire tools for evaluating the restorative potential of environments or images on the basis of these factors (e.g. Hartig, Korpela, Evans, & Garling, 1997; Laumann, Garling, & Stormark, 2001). Interestingly, "perceived restorativeness potential," as assessed by participant ratings, were found to be significantly predicted by compatibility, being away, and to a lesser degree, extent; fascination was not a significant predictor of perceived restorativeness, though it was a significant predictor of image preference (Herzog, Maguire, & Nebel, 2003). It should be noted, however, that all of these factors are very highly correlated with each other.

Exposure to natural environments has also been shown to improve children's ability to concentrate and pay attention. In a large survey study, typical symptoms of attention-deficit/hyperactivity disorder (ADHD; difficulty remaining focused on unappealing tasks, difficulty in completing tasks, difficulty listening and following directions and difficulty in resisting distractions) were lower for children who spent more time in "green" outdoor settings, across a wide variety of age groups, family incomes, community types and regions, and children both with and without ADHD diagnoses (Kuo & Taylor, 2004). In a direct experimental manipulation, children with an ADHD diagnosis who were given a 20-minute walk in a city park performed significantly better on a backwards digit span task than children given a walk in a different well-kept urban setting, with an effect size similar to that observed with a popular ADHD medication (Taylor & Kuo, 2009).

These two potential mechanisms – a direct effect on physiological stress and mood, and the restoration of directed attention, may both play important roles. Although negative valence and elevated physiological arousal often co-occur with attentional fatigue, it is not always the case, and the relationship between these states is not clear. Ulrich claims that physiological stress is a cause of deficits in attention, whereas S. Kaplan (1995) claim that a depletion of directed attention capacity can lead to psychological stress, and that deficits of directed attention can occur in the absence of effects on mood (e.g. Tennessen & Cimprich, 1995). It is possible that physiological stress and depletion of attentional resources can occur simultaneously, independently, or that one can lead to the other, and that the mechanism of restoration may depend on what conditions are present.

It has also been suggested that restorative effects on attention and stress may have different timescales. Attentional fatigue may be slower to develop, and may also be slower to recover (Hartig, Evans, Jamner, Davis, & Garling, 2003; S. Kaplan, 1995). The physiological effects of restorative environments may occur relatively quickly (4-5 minutes), followed by emotional effects (~10 minutes), and at the longest timescale, effects on attention and performance (e.g. 20+ minutes; Hartig et al., 2003; Hartig et al., 1991).

There are a few aspects of this research are particularly relevant for considering sensory stimulation augmentation techniques and worth exploring further. First, S. Kaplan (1995) claims that sleep is not sufficient to restore directed attention, though he presents no experimental data is presented to support this claim. It would be important to directly test whether sleep and exposure to natural environments have non-overlapping benefits for aspects of mental fatigue and performance.

Second, the use of sensory stimulation as a countermeasure during LDSM relies critically on identifying what features are necessary to achieve a restorative effect. As is clear from the research cited above, encounters with pictures and movies of natural environments, not solely first-hand immersive experience, can have restorative effects. For example, Kweon, Ulrich, Walker, and Tassinary (2008) reported that even art posters depicting nature paintings that were hung in an office environment led to larger reductions in reported anger and stress following a stress-inducing task than did posters of abstract art (particularly in male participants). In a study directly contrasting thirty minutes of seated relaxation in a natural environment with relaxation in an indoor simulation of the same natural environment (photographs of the same park, from the same locations; Kjellgren & Buhrkall, 2010) found that both environments were associated with reductions in self-reported and physiological measures (blood pressure, pulse) of stress, but that relaxation in the real natural environment was additionally associated with greater energy and reports of "altered states of consciousness," such as those observed during relaxation in flotation tanks. However, subjective reports collected from the observers (who were individuals that self-identified as suffering from stress) also revealed that many of them were irritated by the simulation, and longed to be out experiencing nature firsthand.

The degree to which a simulation of nature can approach actual experiences of nature is likely to be of critical importance. In the extreme, a fully immersive, convincing, high resolution, multi-sensory and highly responsive simulation environment that allows for naturalistic movement and interaction would be expected to have the same benefits as experiences with actual nature. However, the relative importance (and critical thresholds) for the many variables that distinguish reality from simulation has not been extensively tested. In a review of a series of experiments comparing "technological" nature to experiences with actual nature, Kahn, Severson, and Ruckert (2009) reported that viewing a live feed of an outdoor view on an HDTV screen led to improvements in psychological well-being, cognitive functioning, and connection to the natural world when compared to having no outdoor view at all. However, looking out an actual window was correlated with recovery from low-level stress (measured using heart-rate), whereas looking at the HDTV screen view showed no difference in heart-rate recovery when compared to looking at a blank wall (Kahn et al., 2009). A test of screen size on the restorative effects of watching a nature film (following a stressor task) found a greater decrease in heart rate during the first few minutes when viewing a large image (35° visual angle) than when viewing a smaller image of the same movie (15° visual angle), as well as a marginal effect on skin conductance (De Kort, Meijnders, Sponselee, & Ijsselsteijn, 2006). Interestingly, no effect was found on self-report measures meant to assess degree of immersion, suggesting that differences in the physiological effects of restorative stimuli may not always be available to conscious introspection.

A related issue is the degree to which indoor plant life can bestow restorative effects. In a review of the relevant literature, Bringslimark, Hartig, and Patil (2009) conclude that while there is evidence to suggest that indoor plants are associated with stress-reduction and an increase in pain tolerance, the findings are quite mixed, partly due to the heterogeneous nature of the methodologies employed. Raanaas, Evensen, Rich, Sjostrom, and Patil (2011) found that study participants seated in an office with four plants showed significantly better performance than participants in the identical office without plants on a reading span task designed to measure attentional capacity. Importantly, performance did not differ upon immediately entering the room, but the two groups showed significant divergence after being in the room for fifteen minutes (while performing a proofreading task).

Other than the studies previously mentioned that explored the factors of Kaplans' ART model, the content of restorative natural environments is another major variable that has not been well explored (Velarde, Fry, & Tviet, 2007). In one recent study, Gatersleben and Andrews (2013) reported that "prospect," the property of openness and ability to see a wide expanse, increases the restorative properties of a scene, but that "refuge," the property of being enclosed and protected, decreases a scenes restorative properties, both in lab and real setting. The authors suggest that certain scenes high in refuge (e.g. a forest scene) may, in fact, increase the requirement for environmental monitoring (though this should be distinguished from the presence of close-range obstructions).

Combining exposure to simulated restorative environments with exercise is a promising potential countermeasure, and the existing literature suggests that this combination may be synergistically beneficial. Exercising on a treadmill while viewing pleasant rural scenes led to significant reductions in blood pressure and significant increases on measures of self-esteem and mood, above and beyond the effects of exercise alone, and moreso than viewing pleasant urban scenes or unpleasant scenes of either environment (e.g. fields containing trash, buildings with broken windows; Pretty, Peacock, Sellens, & Griffin, 2005). A meta-analysis of results from ten studies on "green" exercise (activity in the presence of nature) found large benefits on self-esteem and mood for 5 to 10 minutes of exercise, with diminishing (but still positive) returns for longer durations, with the presence of water being especially effective, and diminishing returns in older populations (Barton & Pretty, 2010).

Adding additional sense modalities to a simulated environment, such as sound and odor, is likely to increase its immersiveness and potential positive benefits. For example, Alvarsson, Wiens, and Nilsson (2010) found that nature sounds, when compared to urban sounds, led to faster physiological and psychological restoration following a stressor. The use of aromatherapy and tree-derived essential oils is associated with faster post-surgery recovery (J. T. Kim et al., 2007) and improved immune function (Li et al., 2012). The scents of lavender, chamomile, and sandalwood can have anxiety-reducing effects, and peppermint, jasmine, and rosemary improve alertness and cognitive performance (Alvarsson et al., 2010).

Brain responses of multi-modal simulated natural environments (e.g. video plus audio) cannot necessarily be predicted from responses to uni-modal stimuli (Hunter et al., 2010; Pheasant, Fisher, Watts, Whitaker, & Horoshenkov, 2010), and care must be taken to prevent unintended negative consequences from the addition of sensory modalities.

In Section 1, we reviewed evidence that engagement in "escapism" coping mechanisms was less predictive of depressive symptoms at a later timepoint than other coping mechanisms (Palinkas & Browner, 1995). It is unknown whether engagement with simulated restorative environments would prove beneficial in a stressful context such as LDSM, where certain stressors cannot be dealt with (e.g. constant noise, threat to life). To the degree that an individual is experiencing stress on account of resource depletion and generalized negative affect, engaging in a restorative environment may be effective. However, stress that is experienced due to imminent danger and threat to life may not be reduced by engagement with restorative environments until the primary stressor can be dealt with. The mismatch between the cause of stress and the countermeasure, as well as the potential blocking effects of stress on restoration, may reduce effectiveness.
The concept of "soft" fascination presents a potentially interesting link to work on rumination, depression, and the DMN. S. Kaplan (1995) suggests that "soft" fascination, as opposed to dynamically engaging activities, allow opportunities for reflection. Such states may be related to the degree of correlation between the DMN and other networks underlying attention or perception, as "mind-wandering" has been shown to be tightly linked with activation in the DMN (Andrews-Hanna, Smallwood, & Spreng, 2014). Future studies could explore whether restorative environments affect ruminative behaviors, or alter the coupling of DMN and attention networks.

2.3.4.3 Stress-Inducing Sensory Stimulation. Although it is not the focus of this review, it should be noted that certain forms of sensory stimulation can act as stressors. A salient example that has been previously mentioned is auditory noise. Both intermittent noises (alarms, beeps, bangs) as well as continuous noise have been shown to increase arousal and activate threat monitoring systems (Burow, Day, & Campeau, 2005; M. Kim et al., 2012). Importantly, unlike other forms of constant stimuli, humans do not show adaptation to most forms of constant noise (Frederick & Loewenstein, 1999).

2.3.4.4 Blocking Effects of Stress. The stress response once triggered, can potentially block the positive effects of sensory stimulation. Both acute stress manipulations and chronic stress exposure attenuate responses to positive stimuli in animals (Rygula et al., 2005; Willner, 2005) and in humans (Berenbaum & Connelly, 1993; Bogdan & Pizzagalli, 2006; Bogdan, Santesso, Fagerness, Perlis, & Pizzagalli, 2011; Pizzagalli, Bogdan, Ratner, & Jahn, 2007). For example, women under acute stress produced by threat of shock show blunted reward responsiveness (Bogdan & Pizzagalli, 2006; Bogdan et al., 2011), measures of marital stress are associated with reduced responsiveness to positive images as measured using EMG (Lapate et al., 2014), and cadets undergoing military training report decreased ratings of pleasure in response to positive provocations (Lapate et al., 2014). Individuals reporting higher levels of stress in the recent past show reduced reward learning (Pizzagalli et al., 2007), suggesting that these effects can linger after the termination of an acute stressor. Following acute stress manipulation, adults selectively allocate attentional resources toward threat-relevant stimuli, suggesting that blunted positive affect is also accompanied by increased negative affect (Mogg, Mathews, Bird, & Macgregor-Morris, 1990).

Resiliency, then, may critically involve both the ability to recover from negative provocation faster, and to prolong positive emotional responses (within a healthy range; Davidson, 2000; Thompson, 1994). The timecourse of emotional responding during and after an emotional stimulus presentation, rather than its magnitude, may be a hallmark of resilience (Davidson, 2000). As will be further explored below, the blunted responsiveness to positive events following onset of the stress response may become a feedback cycle, leading to a persistent state during which the normally stress-reducing effects of restorative sensory stimulation may become ineffective.

2.3.5 Mood Systems Integrate and Maintain Affective States. Mood is differentiated from emotions in that emotions are generated by specific events and are directed at specific objects, whereas moods can be more long lasting and non-specific. Kahneman (1999) suggests that mood may represent the integration over time of more discrete emotional states. A potential function of mood states is to act as "feeling-based" predictors of the likelihood of positive or negative events (e.g. pleasure, pain) in the near-term future (Morris, 1999). Given an assessment of the availability of resources, the mood system produces feelings that are capable of influencing goal-directed activity. Morris suggests that there is a need for mood to fluctuate, and highlights the strong effect that unexpected positives can have on mood (Morris, 1999).

Although a review of the literature on mood disturbances is too vast to review here in detail, there are several findings that may be particularly relevant for LDSM and sensory stimulation augmentation. Anhedonia, a state in which individuals do not appear to get pleasure from experiences that are normally experienced as pleasing, is a core symptom of major depressive disorder (MDD) and several other mood disorders (APA, 1994). However, recent findings have called into question the hypothesis that the anhedonia observed in MDD is due to a dysfunction of feeling pleasure, and suggest that it may instead reflect aberrant reward motivation (e.g. wanting; Der-Avakian & Markou, 2012; Treadway, Buckholtz, Schwartzman, Lambert, & Zald, 2009; Treadway & Zald, 2011). Although serious, long-lasting depression may be highly unlikely to occur amongst a highly motivated and scrutinized crew selected for long-duration spaceflight, more mild forms of depressed mood may be likely, and planning for LDSM missions should take into account an understanding of the relationship between sensory stimulation levels and mood.

In a recent review, Moshe Bar presented a hypothesis linking positive mood with associative processing (Bar, 2009). There is evidence linking positive mood with associative thinking (e.g. Isen, Johnson, Mertz, & Robinson, 1985; Mednick, Mednick, & Jung, 1964) and a shift toward a global focus in attention (Fredrickson, 2004; Gasper & Clore, 2002), and he suggests that there is a link in the opposite direction as well – that associative processing promotes positive mood (Bar, 2009). In particular, Bar suggests that rumination, a self-focused pattern of thought that has been associated with negative mood (Segerstrom, Tsao, Alden, & Craske, 2000) and is prevalent in those with mood and anxiety disorders (Michael, 2006; Nolen-Hoeksema, 2000) is a form of narrow processing, and that broad, associative thinking, which is associated with activity in structures of the medial temporal lobe and anterior regions of the ventral visual pathway, promote positive mood. Such associative thinking could be brought about behaviorally by providing a wide variety of distractions to ruminations (as opposed to the same distractor repeatedly) or performing a mental activity such as reading that promotes broad associative activity. He also suggests that the depression alleviating effects of selective serotonin reuptake inhibitors (SSRIs) and certain forms of transcranial magnetic stimulation may also be, in part, related to broadened MTL associative activity, through neurogenesis or disinhibition of the hippocampus by the medial prefrontal cortex (MPFC).

There is an interesting connection between Bar's hypothesis and the findings reported above on aesthetically moving responses to artwork. The ventromedial MPFC, hippocampus and parahippocampal cortex (PHC) are all nodes of the "medial temporal lobe subsystem" of the DMN (Andrews-Hanna et al., 2010). Abnormal functioning of the DMN has been linked to depression (Davidson, Pizzagalli, Nitschke, & Putnam, 2002; Ressler & Mayberg, 2007; Sheline, Gado, & Kraemer, 2003), with depressed patients showing sustained activity in DMN regions (particularly MPFC) during externally focused tasks that normally lead to suppression (Sheline, Price, Yan, & Mintun, 2010). Sheline also reports that the hippocampus and PHC also show higher activation to looking at negative images in depressed patients, even when they are asked to use emotion regulation strategies to reduce the emotional response to the images (Sheline et al., 2010).

Taken together, these findings are consistent with the hypothesis that in depression, the ventral MPFC and other portions of the DMN may be overactive and entirely "disconnected" from external events, and that this leads to MTL activity that is narrowly focused. On the other hand, normal individuals show DMN deactivation patterns that are more responsive to external events, and when normal individuals view artworks, the DMN may be engaged in a manner that allows for broadly associative activity in MTL regions. Whether depressed patients show a different pattern of response to artworks is unknown – one possibility is that moving aesthetic experiences may counteract reduced positive affect through the promotion of broadly associative thought.

However, it is also possible that depression, or ruminative though patterns more generally, may "block" any potential mood-enhancing effects of sensory stimulation that aims to promote broadly associative thought. Similar to the findings reported above of a link between stress and reduced responsivity to positive events, there is also evidence that depressed mood is associated with reduced responding to positive events. Emotional disturbances, and depression in particular, show robust decreases in responding to positive stimuli, and these decreases appear to be more specific to depression and consistent than changes in the domain of negative emotional responses (Bylsma, Morris, & Rottenberg, 2008; Mineka, Watson, & Clark, 1998; D. Watson, Gamez, & Simms, 2005; D. Watson & Naragon-Gainey, 2010). Interestingly, several authors have found evidence that although depressed individuals show an *initial* response to positive stimuli that is comparable to control participants, this positive affect is not *maintained* and instead shows steeper declines after a stimulus (e.g. a humorous movie) or over the course of an experimental session (Heller et al., 2009; McMakin, Santiago, & Shirk, 2009). This decline is accompanied by a reduction in activity in the ventral striatum (nucleus accumbens; Heller et al., 2009). Other studies have also found decreased engagement of the caudate and ventral striatum in depressed individuals during the processing of rewards (Pizzagalli et al., 2009), and anhedonic symptoms correlate with caudate volume in both normal and depressed samples (Harvey, Pruessner, Czechowska, & Lepage, 2007).

This reduced maintenance of responding to positive events, which appears to be a hallmark of a depressogenic affective style, may be a result of a functional "disconnection" of reward centers (e.g. ventral striatum and ventral pallidum) from regions of the prefrontal cortex (medial frontal gyrus, MFG; Heller et al., 2009). Although the MFG is not a part of the DMN, these findings do provide convergent evidence that depressed mood may involve reduced connectivity between brain networks that normally allow for information about the external world to be experienced as positive, to affect emotion, and to be maintained. Anhedonia, then, may represent a state of disconnection between sensory systems and positive valence systems, potentially due to the blocking effects of an overly active, narrowly focused DMN preventing the associative activity and subsequent pleasure normally associated with sensory experiences, resulting in a decreased drive to seek out such experiences. As a consequence, there is a danger that in an isolated environment such depressed mood states may become self-sustaining and resistant to intervention. Whether a prolonged lack of sensory experiences leading to broad associative activity in normal populations can lead to a state of disconnection, subsequent anhedonia and depressed mood is unknown.

2.4 SUMMARY

Low-Level Effects

- Neural plasticity happens at multiple levels of the nervous system.

- Changes in representations of low-level features of the environment can occur through perceptual learning, and are thought to be "gated" to prevent maladaptive changes.

Perception

- The nervous system can be viewed as a set of hierarchically arranged perception-action cycles. There are both "fast" (automatic, inflexible) and "slow" (deliberate, flexible) routes to action.
- Perceptual systems extract information about features present in the environment through a hierarchical arrangement of processing stages that represent increasingly invariant features. There are separate visual pathways for identification and interaction that send outputs to systems for memory, prediction, reward processing, decision making and action planning. Within these systems, information from the environment flows in a "bottom-up" manner, and expectations give rise to "top-down" modulation.

Cognition

- Reduced sensory stimulation likely affects the balance between exogenous and endogenous attention mechanisms.
- The roles of systems for memory, executive function and conscious awareness in the effects of reduced sensory stimulation are unclear.

Affect and Emotion

- Research on pleasure and reward systems suggests dissociation between systems mediating "liking" and "wanting."
- There is a biological drive to acquire novel yet highly interpretable information that is separate from reinforcement learning mechanisms. This drive may be implemented via connections from the ventral visual pathway to reward systems, working in concert with regions controlling goal-oriented behavior.
- Repeated exposure to a stimulus leads to changes in perceptual and affective responses. Under most circumstances, this is a reduction in preference (hedonic adaptation). This may be related to neural repetition suppression. Increases in preference can also be seen, potentially before cognitive mastery has been achieved.
- Semantic associations (meaning) are of critical importance for the pleasure derived from sensory experiences.
- Emotional states elicit changes in the control of behavior or thought. The amygdala, orbitofrontal cortex and hippocampus form core regions for emotional responding, along with output pathways in the ventral striatum and hypothalamus for influencing behavior. There are several frameworks for understanding emotion that emphasize either arousal and valence, discrete emotional states, or emotions as sets of appraisals of an event.

- There are a class of "knowledge-based" emotions (interest, confusion, surprise, awe, wonder, beauty) that are linked to appraisals of novelty and understanding. These include aesthetic emotions, such as those experienced when one is moved by artwork or music. Aesthetic experience involves the interaction of perceptual systems with value/reward networks, networks for understanding, and networks involved in internally-directed mentation (e.g. the "Default Mode Network"). Activation of the DMN may be a hallmark of aesthetically moving experiences, and potentially other types of inspirational (salutogenic) experiences.

Stress and Coping

- Sensory stimulation and stress are related in at least three ways: certain forms of sensory stimulation may induce stress; a *lack* of sensory stimulation may be experienced as stressful; certain forms of sensory stimulation may aid in coping with stress.
- The behavioral control column (BCC) represents a set of hypothalamic and brainstem regions by which an unmet information foraging drive may lead to activation of the stress response
- There is a body of literature suggesting that exposure to natural environments can be "restorative." Spending time in natural (as opposed to urban settings) can lead to reductions in stress, improvements in directed attention, improvements in mood, and faster recovery from medical issues. Some evidence shows that more reduced stimuli, such as movies or images, can have some restorative effects, though these results are mixed, and it is unclear what parameters determine whether restorative effects are observed. Two theories have been proposed - one positing a direct effect of natural environments on stress and mood, and another suggesting a mediating role of directed attention fatigue and restoration.
- It is possible that sleep may not be necessary, nor sufficient, to restore all situations of mental fatigue related to depletion of directed attention.
- Stress can potentially block the positive effects of sensory stimulation.
- Anhedonia (lack of pleasure from experiences normally experienced as pleasurable) is a core trait of depression. There may be a potential connection between anhedonia and abnormal functional connectivity in the DMN, resulting in a disconnection of sensory systems and reward systems. Such effects may be related to perseverative internally-directed thought (rumination) and a lack of broadly associative processing.

SECTION 3: MEASUREMENT

Framing Question: How does one measure and quantify whether the level of sensory stimulation for an individual is adequate or inadequate, and how can the effectiveness of particular stimuli in meeting specific goals of sensory stimulation augmentation be evaluated?

In this section, we will review general approaches and available techniques for quantifying sensory stimulation and its effects, and for identifying whether an individual is in need of a sensory stimulation countermeasure. First, we will identify constructs that need to be quantified and measured. We will present behavioral and self-report approaches, which may be considered to be the least invasive. This includes survey instruments, computer based tasks measuring cognitive performance or emotional responding, and adaptive tasks or interactions with computerized agents. We then consider more invasive measurement approaches that make use of physiological signals such as heart rate, galvanic skin response, or the activation of muscles, followed by consideration of video-based signals, such as eyetracking, pupillometry, and facial emotion expression recognition. Third, we consider two techniques for measuring brain signals that are suitable for use in space – EEG and fNIRS. Finally, we consider a range of techniques and approaches for measuring individual differences that could be used for crew selection and the development of personalized countermeasures.

3.1 CONSTRUCTS RELEVANT FOR SENSORY STIMULATION

There are several classes of constructs that are relevant to measure within the context of sensory stimulation augmentation. With regard to potential countermeasures, it is important to characterize stimuli in a manner that allows for the development of “effectiveness” and “dosage” recommendations. With respect to astronauts, sensitive measures are needed to quantify real-time (acute) engagement with and responses to sensory stimulation, as are measures of the state of an individual (e.g. mood, chronic stress) that would signal a need for specific countermeasures and track the cumulative effects of the sensory environment. Finally, there is also a need for “trait” measures that make meaningful distinctions between individuals and can be used for astronaut selection and development of personalized countermeasures. Measurement of individual differences will be addressed in the last part of this section.

3.1.1 Generating and Quantifying Stimuli. Predicting the effects of sensory countermeasures on perception, cognition, mood and well-being requires that sensory stimuli be understood and quantified at multiple levels of analysis. Low-level stimulus properties (e.g. color, resolution, bitrate) are important for understanding the perceived quality of an image or sound (and presumably, of a smell or tactile stimulus as well) as well as the degree of immersiveness produced by the stimulus. Psychophysical techniques that have been used for over a century to quantify people's sensitivity to perceptual phenomenon include the measurement of psychometric curves (a mapping between physical stimulus magnitude and perceived magnitude), contrast thresholds and spatial or temporal acuity.

There currently exist a number of models derived from this large body of work that can quantify stimuli in terms of parameters that are of importance to human perceptual systems, and that provide useful frameworks for predicting perceived quality and immersiveness. In the visual domain, the L*a*b color space model, which is based on opponent models of human color vision, computes contrast in luminance (L), red-green (a) and blue-yellow (b) channels (Wyszecki & Stiles, 1982). Models of the existence of spatial detail at multiple scales, such as Hmax (Riesenhuber & Poggio, 1999) and Simoncelli's steerable-pyramid model (Simoncelli & Freeman, 1995), mimic important aspects of early spatial visual processing. Video is often measured using a motion-energy model that mimics what is known about human motion perception (Adelson & Bergen, 1985). Information derived from these models has been used to great success in industry, from automatic color correction of photographs and movies to image, sound, and video encoding algorithms (e.g. jpeg, mp3, mpeg). Existing compression algorithms take advantage of the known sensitivities of the visual system in order to preserve information that is critical for perceived stimulus quality (e.g. no noticeable artifacts) in the most compact form possible. This allows for computational power, effort and bandwidth to be focused on those features, while unimportant features can be discarded.

Within the image and video analysis communities, a number of "quality of experience" (QoE) metrics have been developed, including direct metrics that correlate an original signal with an encoded signal on a number of measures (e.g. blurriness, global noise, block distortions) and indirect measures such as delivery time of a stimulus over the network (Serral-Gracia et al., 2010).

As was outlined in Section 2, affective responses to sensory stimuli depend heavily on higher-level stimulus features. Unlike for lower-level features, there are no fully implemented generative models of higher-level information that can be used to predict a person's subjective "quality of experience" or engagement, let alone subjective information content, aesthetic response, or restorative potential. Current work on modeling object recognition and scene gist include the hierarchical modeling of geometric primitives (e.g. Biederman, 2013; Hummel & Biederman, 1992), and appearance- and feature- based matching (e.g. Serre, Oliva, & Poggio, 2007). Yet despite the continued work on theoretical and practical approaches for how to model object recognition and extraction of semantic information (see DiCarlo, Zoccolan, & Rust, 2012), most of these approaches can, at best, derive a static or "average" model. As was reviewed in Section 2, the later stages of perceptual pathways are more plastic, and therefore more individual, than are early, lower-level stages. Affective responses to content, then, are more dependent on an individual's personal history, and will require dynamic models that can capture the current state of a person's knowledge and understanding.

In lieu of detailed models of human perceptual processing, one promising direction is to look for informational measures that capture the hierarchical nature of perception and recognition processes and use such measures to predict the degree to which a sensory experience will be engaging, informative, aesthetically pleasing, or restorative. As a starting point, consider Shannon entropy, which is the average number of bits needed to encode one symbol in a message, and is related to its ability to be compressed. Jpeg encoding, for example, uses a static basis set derived from research on human perception. Although Shannon's entropy measure is primarily used for describing the quantity and readability of data and is generally insensitive to the importance or meaning of a message, it could be possible to create a similar measure of hierarchical information for the *content* of a message.

Several related theories have been developed that may capture important aspects of the hierarchical nature of perceptual and semantic content. The first, algorithmic information theory (AIT), was originally developed by Solomonoff and Kolmogorov and later expanded by Chaitin, and combines the concept of compression from Shannon's information theory with the computational principles of algorithms developed by Turing. The fundamental idea of AIT is to quantify the shortest possible algorithm (fewest bits) that can produce a specific message. For example, the letter string 'ababababababababababababababab' can be expressed as 'repeat ab 15 times'. A stimulus that is entirely random (e.g. white noise), cannot be expressed in any more compact form, whereas an image with structure in it can. AIT is currently being used to model and quantify when a pattern is "surprising" and how the new information is incorporated into knowledge (Maguire, Moser, Maguire, & Keane, 2013). This approach could potentially be adapted to model *subjective* novelty and the 'click of comprehension' that occurs when a person detects a pattern or explanation that allows for them to make sense of a previously incomprehensible experience.

A related concept is *mutual information*, which expresses the degree to which one object (or message, etc.) is simpler to encode when presented along with a second message (e.g. the amount of information in common between two random variables). Integrated information theory (Balduzzi & Tononi, 2009) is a mathematical approach for evaluating a network of interacting elements that captures key aspects of mutual information and extends beyond it to describing information that is *only* present when elements are considered together. "Integrated" information is the amount of information that is transmitted by a system considered as a whole above the information that is transmitted by its parts. As an example, consider a network of interacting elements that can capture information about people that you know. One subset of elements in the network may capture information about your friend Amy, while another subset may capture information about your friend Bob. If you already know that Bob and Amy know each other, then there likely already exists a link between these two networks, and seeing Bob and Amy together produces a global state in the network considered as a whole that does not carry any new information. However, if you know Bob and Amy from very different social circles, then the global state of the network produced by seeing them together contains information that is not captured by the state of each network individually. Using these mathematical frameworks along with controlled behavioral experiments, it may be possible to develop an informational science that models the hierarchical nature of human perception and understanding, and allows predictions of knowledge-based emotions (surprise, aesthetic appreciation) based on measurements of a stimulus and a model of an observer's internal knowledge structures.

Despite the fact that prescriptive quantitative approaches to modeling positive affective and aesthetic responses to stimuli (information foraging) have a long way to go, there are a variety of content specific machine learning methods for making predictions about what people will like that are based on a set of (often) hand-coded features. In Section 4, we will further discuss some of these existing technologies for creating personalized stimulus profiles (e.g. Netflix, Pandora, Art.sy).

3.1.2 Measuring (Acute) Stimulation Levels and Real-Time Engagement. Relevant constructs for measuring how much sensory stimulation a person is currently experiencing include a) perceived stimulus intensity, b) arousal, calmness and anxiety, c) boredom and stimulus driven ("bottom-up") attentional capture, d) curiosity and surprise, and e) engagement. Relevant constructs for assessing the affective impact of sensory stimulation include a) initial responsiveness to reward (liking), b) approach motivation (wanting), and c) aesthetic appreciation (e.g. beauty, sublimity, awe, wonder).

Potential measures for these constructs include:

- logging time interacting with countermeasures
- survey, self-report or observational measures of the current sensory environment ("state" measures)
- real-time behavioral measures of responses to specific stimuli, such as liking responses, willingness to work for a stimulus, and measurement of thresholds
- physiological measures, such as heart rate, respiration, galvanic skin response (GSR) and automatic facial muscle responses (electromyography; EMG)
- video measures such as eyetracking, pupillometry, facial expression analysis
- EEG and fNIRS

3.1.3 Measuring (Chronic) Cumulative Effects on Perception, Cognition, Well-Being. Relevant constructs for measuring the cumulative effects of one's sensory environment include a) perceptual thresholds, b) attentional capacity, c) executive functioning, d) fatigue, e) stress, f) emotional responding and coping, g) mood (anhedonia, dysphoria, happiness, anxiety) and h) well-being.

Potential measures for these constructs include:

- measuring perceptual changes (thresholds) using self-report or computer-based tasks, psychophysiological responses (e.g. EMG), EEG
- detecting neuroplastic changes across the cortex using EEG or fNIRS
- measuring attention and executive functioning using computer based tasks
- measuring stress, anxiety & fatigue using self-report, computer-based tasks (e.g. reaction times, cognitive assessments), physiology (blood or urine samples), psychophysiological responses (blood pressure, GSR startle response, EMG responsiveness) and EEG
- measuring emotional responding, coping, mood and well-being using self report, computer-based tasks, psychophysiology, video-based facial responding, EEG and fNIRS

In Section 4, we propose a taxonomy of needs that are met by sensory stimulation. A potentially useful framework for understanding the chronic effects of environmental sensory stimulation levels could be to focus on development of measures that can distinguish these need states. Further research is needed to understand whether there are consistent behavioral, physiological or neural markers for these need states.

One very salient dichotomy in the needs satisfied by sensory stimulation is the opposition between the needs for information foraging and restoration. One is active, the other is more passive. One is about seeking and variety, while the other may require safety, calm, and potentially even an aspect of familiarity. This dichotomy, which is echoed in Peldszus et al. (2014) recent review of monotony in deep space missions, may be related to other work in social psychology that emphasizes a difference between motivational states with a “promotion” versus a “prevention” focus (Armstrong & Detweiler-Bedell, 2008). If this relationship holds, this would suggest that *state* measures of behavioral approach and behavioral inhibition (e.g. similar to BIS/BAS trait measure, see below), could hold promise as a central component of distinguishing need states of information foraging and restoration.

3.2 BEHAVIOR AND SELF-REPORT

Most behavioral and self-report measures require no special equipment beyond a computer. They can be used repeatedly with minimal setup.

Self-report questionnaires, which typically consist of a set of items that a person reads and responds to on a Likert scale or visual analog scale (e.g. rate how much you agree with this statement on a 1 to 7 scale), are extremely simple to collect. However, there are a number of fundamental problems with such instruments. Although many test instruments have been subjected to test-retest reliability testing, it is often not clear to what degree they actually serve as valid measures of the constructs they are intended to target. Some of this difficulty comes from the fact that many internal states are inherently inaccessible to self-reflection – there are many well-documented cases in which individuals' beliefs (e.g. about how they would behave, what they might choose, or even about the causes of their own actions) diverge significantly from information derived from more objective measures. Reliability varies, and internal reliability is sometimes prized over construct validity.

Laboratory-derived behavioral tasks, such as those that measure percent correct, reaction times, or ask observers to assess real-time, trialwise preferences, beliefs or emotional states (as opposed to hypothetical questions about preferences, beliefs or emotional states) generally have higher construct validity than self-report measures, and should be used when possible. However, there are a number of constructs relevant for sensory stimulation and emotional responses to sensory stimulation for which validated laboratory-based tasks exist.

In this section, we will discuss some of the relevant self-report measures and laboratory-based tasks for measuring responses to specific stimuli and assessing the "state" of an individual. "Trait" measures will be addressed below in the section on individual differences.

3.2.1 Responses to Specific Stimuli. Specific stimuli, such as images, videos, music, smells, etc. can be characterized using a variety of perceptual and affective tasks. At a perceptual level, thresholds for detection can be measured using present/absent designs and "just-noticeable-differences" (e.g. acuity) can be measured using forced choice paired comparison experiments. In addition, there are a host of measures that can be used to get at stimulus saliency and attention, such as "change blindness" tasks in which an observer is asked to identify a change that has been made between an original stimulus and a modified version (e.g. Rensink, O'Regan, & Clark, 1997; Simons & Rensink, 2005) and search tasks to assess feature "popout" (e.g. Treisman, 1985; Wolfe, 1994).

A number of behavioral paradigms have been used to measure positive affective responses. One common paradigm is to ask people to make rating judgments of liking, interestingness, pleasure, how moving a stimulus is, etc. Forced-choice paired comparisons can also be used, which an observer has to choose which of two stimuli they prefer (e.g. Vessel & Rubin, 2010). Although this method requires more trials, it provides data that is free of any potential bias in response-category criterion, and also allows for a number of quantitative analyses to be performed, such as detection violations of transitivity or the use of multi-dimensional scaling. Another very useful paradigm couples a rating task to measure "liking" (hedonic impact or "initial responsiveness" to reward) with a scheduleless keypress task to measure "wanting" (approach motivation, willingness-to-work, or incentive salience; (see Aharon et al., 2001). In a visual "liking" task, observers are shown images and then indicate how much they like the stimulus on a rating scale. In the "wanting" task, observers are shown images for a fixed time (e.g. 4 seconds), and if they do nothing, the image will be replaced with a new one after that time. However, the observers can make the image stay on the screen longer by pressing two keys in rapid succession, and can make an image disappear faster by pressing a different set of two keys. Some newer work is also beginning to look at the time constant of *sustained* pleasure as a measure of whether it is aesthetically engaging and moving (Vale & Pelli, 2014).

Laumann et al. (2001) developed a 22-item questionnaire to assess the restorative properties of a stimulus (e.g. photograph, video) based on Kaplan and Kaplan's (1989) Attention Restoration Theory. This test was found to be fairly reliable (Cronbach's α mostly between 0.82 and 0.94, with one exception). While this test is one of the only measures specifically directed at measuring restorativeness, it is unknown to what degree it actually measures the appropriate psychological construct, and it is also laborious to use this entire questionnaire for a large number of stimuli. Questionnaires have also been developed to assess the degree of immersiveness of (headset or screen-based) virtual and digitally rendered environments (see Slater, 1999; Witmer & Singer, 1998).

3.2.2 State Measures

3.2.2.1 Questionnaire and Interview Instruments. As mentioned above, questionnaires are widely used across a variety of populations due to their ease of administration. Despite the caveats raised above regarding reliability and construct validity, psychologists still utilize many such state measurement scales. Below, we will discuss a number of questionnaires that are designed to measure mood constructs, depression, anxiety, anhedonia, attentional functioning, and emotional appropriateness.

Mood. There are a large number of questionnaire and interview-based assessments that are intended to give a general picture of a person's mood. The Positive and Negative Affect Schedule (D. Watson, Clark, & Tellegen, 1988), which was originally developed in 1988, is very frequently used to measure mood states in social and psychological research. Classically, PANAS is made up of two ten-item NA and PA five-point Likert scales. Subtly distinct, PA and NA are treated as independent states. High PA is associated with enthusiasm and alertness within ones environment, while low PA tends to reflect sadness and lethargy. High NA is indicative of distress and displeasure, while low PA might reflect a calmness or lack of distress. Scale intercorrelations and consistency reliabilities rate exceptionally high (Cronbach's α consistency PA = 0.86 - 0.90, NA = 0.84 - 0.87), making the PANAS an efficient measurement tool.

Reports based on multiple, independent dimensions provide more comprehensive descriptions of specific emotional states. The Pleasure, Arousal, Dominance (PAD; Mehrabian, 1995) Model forms a basis for characterizing emotional temperament across three domains: pleasure-displeasure, arousal-nonarousal, and dominance-submissiveness. Trait *pleasure* refers to an individual's characteristic level of pleasure (or displeasure) over time and across a representative variety of situations. *Arousal* refers to a person's mental alertness and physical activity and is typically increased during information-rich events. *Dominance* represents to degree to which a subject feels he or she has influence over a situation, as opposed to being controlled by outside circumstances. Responses are in the form of nine-point Likert ratings and are found to be both reliable and consistent (Cronbach's α internal consistency of 0.97 for state pleasure, 0.89 for arousal, 0.80 for dominance).

Several other mood measures provide similar information. The State-Trait Emotion Measure (STEM) distinguishes situational from sustained emotional valance (Levine et al., 2011). Scores are computed for discrete emotion feelings, and aggregate scores are also generated for positive and negative affect. The Mood-State Introspection Scale (MIS) asks about 16 mood-adjective (e.g., are you "happy?") and is used to compute overall measures of pleasant-unpleasant and aroused-calm (Mayer & Gaschke, 1988). The Profile of Mood States (POMS; McNair, Droppleman, & Lorr, 1971) consists of 65 self-report items, generates subscores for anger, confusion, depression, fatigue, tension and vigor, and has a reported consistency of between 0.63 and 0.96.

Depression. Depression symptomatology will be primarily addressed in the trait section. However, the Beck Depression Inventory (BDI) is occasionally used as a state measure. It is a 21-item self-report questionnaire that measures characteristic attitudes and symptoms, and has medium to high internal consistency (average Cronbach's α = 0.86; Beck, Erbaugh, Ward, Mock, & Mendelsohn, 1961; Beck, Steer, & Carbin, 1988). Specific questions in the Beck are sometimes used as measures of anhedonia or dysphoria.

Anxiety. The State-Trait Anxiety Inventory (STAI; Spielberger, Gorsuch, & Lushene, 1970) rates a subject's overall anxiety, separately considering state-specific anxiety (i.e., temporary stress resulting from a particular –usually dangerous— situations) and trait-specific anxiety (i.e., chronic stress during everyday situations). It can be used in clinical settings to diagnose anxiety and distinguish it from depressive syndromes. Typically, two sections (state and trait) each consist of twenty, four-point Likert ratings. Another notable scale, the Beck Anxiety Inventory (BAI; Beck et al., 1988), measures *prolonged* states of anxiety. The BAI is a 21-item self-reporting tool used to measure clinical anxiety, distinguished from depression (for many other scales, the distinction between anxiety and depression is unclear). It, too, is praised for its validity and consistency with other scales (internal consistency Cronbach's α = 0.90; Beck & Steer, 1993). When used together, the BDI and the BAI can be useful for distinguishing depression from anxiety.

Pleasure and Anhedonia. Given the relevance of pleasure for sensory stimulation, we will highlight a number of the scales that have been developed to measure aspects of pleasure and anhedonia (lack of pleasure).

The Snaith-Hamilton Pleasure Scale (SHAPS; Snaith et al., 1995) is a 14-item self-report anhedonia scale measuring hedonic responses across interests, pastimes, social interactions, sensory experiences, and food and drink. Similarly, the Fawcett-Clark Pleasure Capacity Scale (FCPS) is a 36-item self-report questionnaire on which participants rate the degree to which they believe they would enjoy specific hypothetical pleasurable situations (e.g., "You sit watching a beautiful sunset in an isolated, untouched part of the world"). The Chapman Physical Anhedonia Scale (CPAS) is a 61-item true-false questionnaire that assesses the degree to which a person is experiencing reductions in pleasure from physical stimuli, such as eating, feeling, sex, smell and sounds (Chapman & Chapman, 1978; Chapman, Chapman, & Raulin, 1976), whereas the Chapman Social Anhedonia Scale (CSAS) is a 40-item true-false questionnaire intended to measure a loss of pleasure related specifically to social interactions with people, such as talking or sharing emotions (Eckblad, Chapman, Chapman, & Mishlove, 1982). Both have internal consistency values of $\alpha = 0.85$.

More recently, the Temporal Experience of Pleasure Scale (TEPS; Gard, Gard, Kring, & John, 2006) has been developed in an attempt to distinguish *anticipatory* pleasure ("wanting" more of a pleasurable stimulus) from *consummatory* pleasure (satiation from "liking" a current pleasurable stimulus). This distinction is important in understanding predicting motivating, goal-directed behaviors associated with anticipation and "wanting." The TEPS is an 18-item self-report questionnaire (8 consummatory, 10 anticipatory) on which observers introspect about how much they *have* enjoyed certain activities, or how much they would *anticipate* certain rewarding activities. It has a reported internal consistency of 0.71 – 0.79 and a test-retest reliability of 0.75-0.81.

Despite the number of different scales for measuring pleasure and anhedonia, they all suffer from a major drawback, which is that introspection about whether a person enjoys, or would enjoy, certain hypothetical situations, is vastly different from measuring whether they actually do experience pleasure or craving for specific experiences. It is entirely possible that an individual with a mood disorder may believe they would enjoy a beautiful sunset, but if actually in that situation, may not. The converse may also occur (e.g. a belief that one would enjoy something, but then no actual experience of pleasure). In the next section on laboratory-based measures, we present current attempts to develop measures of pleasure and anhedonia that are not based on introspective imagining of hypothetical situations.

Attention. Questionnaires like the Attentional Control Scale (ACS; Derryberry & Reed, 2002) reliably measure both attentional focusing (directed concentration on one task) and attentional shifting (the ability to switch from one task to another). In addition to attentional effects on anxiety states, proper attentional control is important for executive functions like learning and memory. The Mindful Attention Awareness Scale (MAAS; Van Dam, Earleywine, & Borders, 2010) is a 15-item questionnaire that measures "dispositional mindfulness" and has been used to measure changes in attention related to the effects of meditation and mindfulness-based interventions (MBI).

3.2.2.2 Laboratory-Based Tasks.

Sensory Thresholds. Although there is currently little evidence to suggest that reduced sensory stimulation in adults results in any changes in perceptual sensitivity, it will be important for future analog studies and LDSM missions to test for changes in sensitivity over durations that have so far not been tested. This is particularly the case for perceptual analyses that contribute to the maintenance of homeostatic mechanisms and for action guidance, as these systems retain more plasticity in adulthood.

The primary psychophysical method for testing a perceptual sensitivity is to establish a threshold for detection. A number of algorithms for adaptively establishing thresholds exist (e.g. staircase, QUEST; see A. B. Watson & Pelli, 1983). These methods can be easily implemented for a variety of stimulus types and complexity, such as tones, spatial patterns, depth cues, odors, etc.. The drawback to such tests is that they require the reliable generation of different levels of stimulation, which may prove challenging during LDSMs for certain sensory phenomenon, such as proprioceptive information.

Contrast sensitivity can also be measured using a simple printed chart (e.g. Pelli Contrast Chart; Pelli, Robson, & Wilkins, 1988), which measures one's ability to read letters of progressively low contrast.

Measuring Cognitive Function. The WinSCAT (Kane, Short, Sipes, & Flynn, 2005), a computerized neurocognitive battery developed by NASA, contains five tests (code substitution, code substitution delayed recognition, delayed matching to sample, mathematical processing, running memory continuous performance) and is sensitive to processing efficiency and working memory function. It is not known whether any aspects of the WinSCAT may be used as a measure a need state for either information foraging or restoration. However, Kane et al. (2005) did present evidence that the WinSCAT is sensitive to fatigue induced by both sleep deprivation and exercise. Future research would be needed to test whether information derived from the WinSCAT could distinguish a need for sleep versus a need for restoration.

The psychomotor vigilance task (PVT) developed by David Dinges is another well-validated measure of vigilance, attention, and psychomotor speed (Dinges, Maislin, & Powell, 1998; Dorrian, Rogers, & Dinges, 2005). Again, it is unknown at this time whether this task could be useful for distinguishing a need for sleep from a sensory stimulation need such as a need for restoration or information foraging.

A number of other laboratory tasks have been used to measure specific aspects of attention that are relevant for restoration. Berman et al. (2008) used a backwards digit-span task in which participants listen to a sequence of digits and are required to repeat them in backwards order. The need for subjects to move items in- and out- of their attentional focus makes this task a measure of directed attention. The same authors also used an attention network task (ANT; Fan, McCandliss, Fossella, Flombaum, & Posner, 2005; Fan et al., 2002), in which participants respond to the direction of a centrally presented arrow, that can be spatially cued and surrounded by incongruent or congruent flanker arrows. This task allows for the computation of measures of orienting attention, alerting attention and executive function (cognitive control).

Directed attention fatigue has also been measured by presenting observers with a bistable stimulus (such as a Necker cube) and measuring their ability to consciously suppress perceptual reversals (e.g. Tennessen & Cimprich, 1995). An increase in the number of perceptual reversals is taken as an indication of poorer directed attention. Binocular rivalry patterns, or moving “plaid” stimuli (2 moving gratings with different orientations) could also be used. This task could also be useful for measuring changes related to various forms of meditation (Carter et al., 2005).

Tasks for Measuring Affect and Mood. Although depression and anhedonia are traditionally thought of as traits and not states, in the context of LDSM the goal would be to track the emergence over time of negative mood states in individuals who may not otherwise be considered to have a depressive phenotype. We will therefore mention a number of tasks that attempt to capture affective responding and could potentially be useful both for measuring long-term mood traits as well as assessing current (state) mood.

A number of tasks are related to the idea of “mood congruency,” which suggests that people are more sensitive to information that is congruent with their mood. For example, there is some evidence for effects of mood on attentional responding and memory for words. Physical anhedonia (as assessed using the CPAS) has been associated with worse recall and recognition of words of varying valence and arousal (Mathews & Barch, 2004). Although there were no clear affects of valence or arousal, a variance analysis suggested that physical anhedonia may have had an influence on subjective experiences of valence for positive stimuli, while social anhedonia may have exerted an influence on subjective experiences of valence for negative stimuli. An older study had found that while healthy controls show a bias to attend to “manic” (positive) words in a tachistoscopic viewing task, depressed and dysphoric individuals do not show such an effect (Gotlib, McLachlan, & Katz, 1988), which would suggest a mild form of mood congruency.

A second area of research has linked aspects of reward responding, particularly using monetary rewards, with dysphoria and depression. In a task where observers were asked to report the length of a cartoon “mouth” on a cartoon face (long vs short), Pizzagalli, Jahn, and O'Shea (2005) found that control subjects developed a response bias over the course of several hundred trials when one of the responses was rewarded at a higher frequency than the other. Patients with depressive symptoms, however (higher BDI scores) did not develop a response bias, and this lack of reward responding predicted subsequent reports of anhedonic symptoms at a later time. Similar results were found in a group of patients diagnosed with MDD (Pizzagalli, Iosifescu, Hallett, Ratner, & Fava, 2008). Brailean, Koster, Hoorelbeke, and De Raedt (2014)used a task in which specific shapes were associated with either wins or losses of money in a conditioning task. Control subjects developed a positive attentional bias toward shapes that were associated with winning, that affected reaction times in a subsequent task where the shapes are presented and observers reported the location of a dot probe (either on or off the shape). Dysphoric patients, however, did not show any bias for the positively rewarding shapes, suggesting that they failed to use information from the recent reinforcement history to guide attention and decision-making (Brailean et al., 2014).

Other authors have suggested that reward responding deficits in depressed patients are due to differences in motivation, not attention or reward-based learning. Using a task in which observers are required to rapidly hit a key in a fixed period of time in order to receive a monetary reward, Treadway and Zald (2011) found that individuals scoring higher on a measure of anhedonia (Chapman Anhedonia Scale) chose fewer “hard” trials that required more effort but resulted in bigger payoffs. This effect was strongest for the highest payoff level. It was also reported that the effects were stronger for women than for men.

This task, or a similar money-based reward task, could be a decent state or trait index of “wanting” and dopamine system function. A number of other labs have also proposed various forms of gambling tasks to measure reward responsiveness and exploration tendency (Huys, Vogelstein, & Dayan, 2008). However, the usefulness of monetary tasks with astronauts, who may not be very motivated to play any computer game for small amounts of money, is unknown. In addition, it is possible that potential effects of reduced sensory stimulation on mood may be better measured by responses to and motivation for sensory stimuli than by measuring motivation for monetary rewards.

In the previous section (*3.2.1 Responses to Specific Stimuli*), we introduced a rating/keypress paradigm for measuring dissociable aspects of positive valence, namely, “liking” and “wanting.” In our laboratory, we have been exploring whether summary statistics derived from an individual’s responses on these tasks could be used as reliable “state” measures of positive valence function, such as whether a person is experiencing suppressed ability to feel pleasure or reduced motivation to seek out sensory stimuli. To date, we have some initial evidence that the *variability* of responses on a rating task with artwork stimuli may be a sensitive measure of state reward responsiveness (Masucci, Corsi-Travali, Neumeister, & Vessel, 2014). Although the relationship between anhedonia, depression, reward, motivation and attention is far from clear, continued research in this area is likely to yield a number of useful paradigms for measuring subtle changes in positive valence functioning before the development of more severe mood symptoms.

3.3 PSYCHOPHYSIOLOGY

Certain physical states of the body, particularly those linked to the sympathetic and parasympathetic divisions of the autonomic nervous system, have been found to be reliable indicators of certain affective and cognitive states. These psychophysiological markers include cardiac rhythms, blood pressure, breathing rate and skin conductance (GSR). For example, peak cardiac acceleration is positively associated with pleasure ratings of images, and skin conductance response magnitude is positive correlated with arousal ratings of images (Lang, Greenwald, Bradley, & Hamm, 1993). In addition, the movements of the corrugator and zygomatic facial muscles, even at a level not detectible to human observers, have been linked to arousal, both positive and negative valence, and anxiety. Corrugator response is higher for more negative images, and zygomatic response is higher for more pleasing images, though this latter effect is mostly driven by only the most pleasing images (Lang et al., 1993; Tichon, Wallis, Rick, & Mavin, 2013) These movements can be detected using electromyography (EMG).

3.3.1 Commercially Available Devices. The measurement of EMG requires that electrodes be attached to the face, and, given the low signal-to-noise ratio, often require a large amount of averaging. This makes EMG less useful as an LDSM measurement technique, given its relatively high invasiveness. Biopac's basic system for measuring physiological signals can measure all of these physiological signals (cardiac rhythms, respiration, GSR, EMG) and is the standard in scientific research.

GSR and cardiac rhythms, however, can be measured from sensors embedded in wristbands, making them much less intrusive and more amenable to repeated, long-term use. A wide variety of commercial products are available that measure physiological signals and are integrated with wearable computers or wireless data transmission. For example, Actigraph (www.actigraphcorp.com), Neumitra (Neuma; www.neumitra.com) and Basis (www.mybasis.com) all make wrist-worn devices with GSR sensors and accelerometers, and BodyMedia (FIT; www.bodymedia.com) makes a similar armband device. Several of these devices also measure temperature (Neuma, FIT, Basis), heart rate (Actigraph, Basis), and heat flux (FIT). The Actigraph also measures ambient light levels and proximity to other Actigraph devices. Sample rates for these devices vary between 10Hz to 100Hz. Some use rechargeable batteries with shorter battery life (e.g. Basis, 4 days), while others have longer battery life using non-rechargeable batteries (e.g. Actigraph, 25 days). All of them wirelessly integrate with mobile apps for reporting data, summary information, and biofeedback.

NASA is already using such devices extensively in both spaceflight and analog environments. Whether or not some information from such devices could be extracted that would be useful for detecting effects of reduced sensory stimulation and a need for sensory augmentation is unknown. However, the work cited above showing that cardiac and skin conductance measures are correlated with affect and arousal ratings of images (Lang et al., 1993) and exposure to nature (S. H. Park & Mattson, 2009) suggest that these easy-to-use devices may provide a simple way of quantifying sensory stimulation needs and responses.

3.4 IMAGE-DERIVED PHYSIOLOGY

A number of informative signals can be derived from video of a person's face or body. Video cameras have been used to track eye gaze position and pupil size since the mid-1970's. More recently, advances in algorithms for face tracking and emotion expression classification have led to the development of systems for measuring emotions from video of a face.

3.4.1 Eyetracking and Pupillometry. The primary method of measuring eye movements and pupil size is to illuminate the eye using an infrared light source and then collecting an image of the eye using a camera with an infrared filter. The reflection of the light source on the cornea (corneal reflection) is the brightest spot in the image, while the pupil is the darkest. These two spots can be identified and tracked, and the combination of their positions allow for the gaze position of the eye to be determined, typically in conjunction with a suitable calibration procedure.

Moment-to-moment gaze fixations reflect overt attention, and are used in a variety of settings to learn about how observers analyze the layout and content of an image or scene. In one approach, regions-of-interest (ROIs) can be defined to calculate the amount of time an observer spends looking at specific features of a stimulus or scene. In another approach, the number or order of fixations is used to infer information about the saliency of objects or locations. Fixation patterns can be compared across different versions of the same image to measure change detection, or across different tasks while observers look at the same image to measure the influence of task set on endogenous attention. Paired comparisons between two side-by-side images can be used to measure a form of interest or preference, and information about decision (choice) variables has been inferred from the proportion of time an observer fixates potential objects of choice (e.g. the Gaze Cascade Effect; Shimojo, Simion, Shimojo, & Scheier, 2003). Proportion of time fixating a media source can also be used as a measure of engagement.

There have also been some studies that report that some aspects of affect, cognition and emotion can be measured from the eyes. There is some initial evidence that fixation duration and saccade rate may correlate with self-reported anxiety (Tichon et al., 2013). Phasic changes in pupil size have been found in response to arousing pictures (Bradley, Miccoli, Escrig, & Lang, 2008), novel stimuli (Steiner & Barry, 2011) and cognitively demanding tasks (Chiew & Braver, 2014), while tonic pupil size may reflect overall arousal level or proactive cognitive control (Chiew & Braver, 2014).

There are a variety of eyetracking systems ranging from highly accurate (0.2° – 0.4° of visual angle) systems with data rates up to 2000Hz that require a subject's head to be stabilized, to more flexible remote screen-mounted or head-mounted systems that have lower accuracy (05 - 1° of visual angle) and lower framerate (e.g. 30-50Hz) but allow for more free movement. Precision eyetracking (e.g. Eyelink 100plus by SR Research, www.sr-research.com) is often performed using only one eye and with subjects' head fixed on a chinrest, whereas remote screen-mounted systems (e.g. SMI's Red500, www.smivision.com, Tobii's Tx300 or T60 XL, www.tobii.com), which can still be quite good, often track two eyes and use some form of head tracking to make eyetracking more robust to head movements at the expense of some accuracy. A number consumer-grade remote systems have been developed and marketed for use with video games and VR environments.

Head mounted systems, where an eyetracker is embedded in a unit that looks like eyeglasses (e.g. Tobii's Glasses 2) or in a VR headset, are intended for wireless use while a person is walking or moving their head around the environment, and often have a camera on the front in order to produce annotated video indicating what a person was seeing and where they were looking.

Given the limited range of usability of remote eyetracking systems (typically 50-75cm, with a tolerance for head movement of 30cm), head mounted systems are the likely solution if eyetracking is desired in a larger environment. However, for monitoring one or more well-defined areas (monitors, workstations), remote cameras would work well and be less intrusive.

Software accompanying eyetracking systems typically offer access to raw eye and head position and pupil size. Some systems also offer some form of automatic artifact rejection, ROI analyses, fixation and saccade detection. If tracking is to be done across multiple different people, it is possible that subject-specific calibrations would need to be stored, and then retrieved in an automatic fashion as different individuals approached a camera.

3.4.2 Facial Expression Analysis. As mentioned above, EMG is an invasive and often difficult measurement technique. In addition, it can only measure the activity of muscles that are specifically targeted by pairs of electrodes. Recent advances in machine vision technology, however, have made it possible to track faces and measure the movement of "facial action units" (portions of the face corresponding to muscle groups) from video streams. Although the accuracy and precision of these systems does not approach the fine sensitivity of EMG, it allows for movements across the entire face to be measured simultaneously from a statically positioned camera.

There currently exist a number of software systems on the market that take video (live stream or pre-recorded) and report the presence of a set of pre-defined emotions and movements (e.g. smiling, happiness, anger, sadness, frustration) on the basis of machine learning algorithms that have been trained on FACS features. Most of these systems are very similar, differing in the number and type of features that are used for identifying and tracking faces (e.g. fiducial points, wavelet features), for extracting the FACS features, and for training subsequent classifiers. We have experience with one of these systems, FACET by Emotient (www.emotient.com/products). This system, and its precursor CERT, were created using technology developed by Marian Bartlett's group at UCSD. In comparison to some of the other systems, it seems to be quite robust to variations in video quality (lighting, resolution, framerate), and Dr. Bartletts' expertise in the psychology of human emotion expression recognition makes her group especially well placed to be on the forefront of the development of increased functionality.

One area of active research is the degree to which facial emotion expression classifiers can be trained to recognize more subtle emotions than anger, surprise or smiling. For example, interest and engagement are two mild emotional states that are thought to have subtle correlates in facial expression (Silvia, 2008; Whitehill, Serpell, Lin, Foster, & Movellan, 2014), though the ability of current implementations of facial expression software to distinguish such states from a neutral state is unclear. A second area of research is examining the degree to which emotion may also be recognized from body signals in addition to the face (Kret, Stekelenburg, Roelofs, & de Gelder, 2013).

3.5 MEASURING BRAIN SIGNALS

3.5.1 Electroencephalography (EEG). Electroencephalography (EEG) is a non-invasive measure of brain activity that involves the recording of spontaneous (typically rhythmic) electrical activity along the scalp. The signals measured by EEG, which have millisecond-range temporal resolution, reflect the summation of synchronized post-synaptic voltage potentials arising from cerebral cortex (see Harmon-Jones & Amodio, 2012 for a review). These electrical signals must be conducted through several layers of tissue (cortex, cerebrospinal fluid, the coverings of the brain, skull and scalp) to reach the surface electrodes, and therefore have quite low spatial resolution and low signal-to-noise ratio.

EEG hardware is typically lightweight, portable, low-cost, has low power requirements, and makes no sound. Although EEG is noninvasive, many EEG systems require the precise placement of many electrodes, and getting high quality signals from each electrode often involves time-consuming procedures for making a low-impedance connection with the scalp, such as abrasion, application of gels, and displacement of hair. However, recent advances in hardware have vastly improved the ease of EEG use in a range of settings, including the development of less-obtrusive caps, wireless data transmission, improved robustness to noise and movement, and improved artifact detection. Additionally, there has been significant development of algorithms for use in real-time and for detection of relevant signals, such as relaxation, engagement, attentional focus, mental fatigue and mood states. This increases EEG's potential usefulness for measuring both acute and chronic effects of sensory stimulation, and as a tool for exploring individual differences.

There are two general approaches to using EEG: continuous measures of rhythmic or transient activity and stimulus-locked event-related potentials (ERP). In both of these approaches, the focus can be a signal derived from one or a few electrodes, or on the spatial distribution of signals across the surface of the scalp. When coupled with anatomical models of a wearer's scalp, skull and brain derived from MRI, this surface data can be used to attempt to localize sources of specific signals in three dimensions. However, source localization is less useful in non-research contexts, where the relevant features of a signal can often be extracted from the signal without knowing its precise source.

3.5.1.1 Continuous Measures. A common method of analyzing EEG data is to convert signals collected in the time domain into a frequency-domain representation that represents the amplitude of signals present at different temporal frequencies. This is often done over short, overlapping epochs of 1 to 2 seconds, whose power spectra are then averaged (Harmon-Jones & Amodio, 2012). Power spectra can then be compared across people or in the same person during or after different manipulations.

Much of the research on EEG frequency spectra suggests that there are five frequency bands that show relationships to psychological variables: delta (1-4 Hz), theta (4-8 Hz), alpha (8-13Hz), beta (13-20 Hz) and gamma (20 Hz and higher). Although more recent work has called these precise divisions into question, they provide a useful framework for discussing relevant findings.

A number of studies suggest that features of alpha band signals, bursting oscillations centered around 10 Hz, are correlated with persistent individual differences in personality and also show differential modulation correlated with affective and cognitive states. Alpha rhythms are largest during relaxed wakefulness with eyes closed and show reduction when eyes are opened, and work from the early and late 20th century suggested that alpha rhythm amplitude reflects relaxation versus anxiety (higher alpha is more relaxed; Garrett & Silver, 1976; Pilgreen, 1995; Rice, Blanchard, & Purcell, 1993). More recently, several theories have positive that alpha oscillations play a role in attentional selection and control through "pulsed inhibition" of ongoing-neural activity, and that higher alpha amplitude is a signal of selective attention (e.g. suppression of distractors), including during internal attention and suppression of external input (Mathewson et al., 2011; Ward, 2003). However, Basar (2012) cautions that alpha waves are not a unitary phenomenon, but represent many processes that can show different effects in different regions of the cortex during different tasks.

Measures of the spectral distribution of alpha frequencies such as peak alpha frequency (PAF, single frequency with highest magnitude) and individual alpha frequency (IAF, "center of gravity" rather than peak) are positively correlated with cognitive capacity or preparedness (attention, arousal, working memory), and differ across individuals (slower in elderly & children, slower in most clinical populations; Angelakis, Lubar, Stathopoulou, & Kounios, 2004). Differences in IAF appear to be relatively stable and correlate with a variety of cognitive measures, such as verbal ability, memory performance and digit span (Grandy et al., 2013). Neurofeedback using PAF in elderly led to improvements in executive function (Angelakis et al., 2007).

Alpha band power has also been used to investigate asymmetries in prefrontal function (alpha power is inversely related to cortical activity; Harmon-Jones & Amodio, 2012). An individuals' general motivational disposition (rather than positive or negatively valenced affect *per se*) is associated with left-right frontal asymmetries in alpha power (left for tendency toward approach behaviors, right for tendency toward withdrawal behaviors; Harmon-Jones, 2004). Similarly, depressed individuals show relatively less left (rather than right) frontal brain alpha (Harmon-Jones & Amodio, 2012). Frontal alpha asymmetries are also sensitive to the state of the individual – higher relative left alpha power is associated with tasting sweet solutions in infants, with making approach-oriented facial expressions (joy and anger vs. disgust and fear), and with approach-oriented emotional states (e.g. anger, determination; Harmon-Jones & Amodio, 2012). Similar results have been found using an analysis technique called event-related desynchronization (ERD), a measure of the time-locked power in the alpha band (P. Gable & Harmon-Jones, 2008).

Several other frequency bands also appear to relate to aspects of cognition and emotion that may be relevant for sensory stimulation augmentation. While central posterior theta has been previously associate with drowsiness (Angelakis et al., 2007), frontal theta band activity reflects aspects of cognitive control. In particular, increases in frontal theta are associated with surprise ("unsigned prediction errors" in the language of reinforcement learning) and subsequent top-down shifts in behavior from habitual (model-free) responses to deliberative, goal-directed behaviors (Cavanagh & Frank, 2014). Gamma band activity has been implicated in feature binding and processing of attended items, and has been hypothesized to reflect mechanisms mediating conscious awareness of one's environment (Ward, 2003).

The collection of continuous measures of EEG is worth considering in an LDSM environment. Alpha activity may be a useful tool for measuring the potential effects of sensory stimulation: measurements of alpha power may be informative about restorative states, while theta band activity may be useful for identifying "informative" stimuli that generate surprise signals. Measurements of frontal alpha asymmetries could be used to measure approach vs. avoid tendencies both during and after sensory stimulation countermeasures. Given its continuous nature, a number of algorithms now exist for automatically extracting summary signals from EEG data in real-time (typically using machine learning approaches). In a demonstration of the potential of this approach, Aspinall, Mavros, Coyne, and Roe (2013) asked participants to walk through busy commercial streets and a city park while recording EEG using an Emotiv EPOC wireless system that automatically calculates constructs of "excitement, frustration, engagement, meditation" from continuous frequency measures (see below). They found that moving from an urban street to a park setting was correlated with reductions in the frustration, engagement and excitement constructs, and with an increase in the meditation construct.

In a study of the crew of the MARS-105 study, Schneider et al. (2010) found that decreases in mood observed over the first 10 weeks of isolation were paralleled by changes in cortical excitability, as measured by activity in both alpha and beta power bands. In addition, exercise led to improvements in mood that were also correlated with increases in alpha and beta band activity. This study provides support for the potential usefulness of EEG for studying the effects of isolation and countermeasure effectiveness.

3.5.1.2 Event-Related Potentials (ERP). Event related potentials (ERP's) are electrical signals generated by the brain that recorded on the scalp in response to an event, such as the presentation of a stimulus or a response. With sampling rates between 250 – 1000 Hz, ERP's can reflect the dynamics of post-synaptic potentials in their native temporal resolution. Raw EEG signals are filtered, aligned to event timing, and averaged over multiple trials (often 30-50 per condition; see Amodio, Bartholow, & Ito, 2014).

Specific peaks and valleys of an ERP response are typically characterized with respect to their order and approximate time of occurrence, and many ERP components have been associated with specific cognitive or emotional processes. Early ERP components reflect stimulus-related processes in the initial stages of sensory hierarchies. For example, the N170 is a signal arising from occipitotemporal cortex (fusiform gyrus and neighboring regions) that reflects early configural/holistic encoding of faces in person perception (e.g. Bentin, Allison, Puce, Perez, & McCarthy, 1996; Eimer, 2000). Both the N2 and P3 (P300, late positive potential) ERP components are very relevant for sensory stimulation, as they reflect aspects of novelty, surprise, prediction error and cognitive control (Cavanagh & Frank, 2014). The P3 in particular has been identified as sensitive to "oddball" tasks in which a stimulus appears in an inconsistent context, and has been used to study aspects of categorization and implicit attitudes (Amodio et al., 2014; Nieuwenhuis, Aston-Jones, & Cohen, 2005). It has also been reported that anhedonic subjects show a smaller P300 than control subjects during a task studying focused attention (Dubal, Pierson, & Jouvent, 2000). However, it is important to keep in mind that individual ERP components likely do not map onto single psychological processes, and may reflect the operation of circuits relevant for numerous information processing operations.

Due to the need for averaging across many trials, ERP's are extremely limited as a real-time measure, and may therefore be less useful in an LDSM context. However, ERP's are likely to continue to be extremely useful for research on the processes involved in perceptual, cognitive, and emotional responses to sensory stimulation. For example, a recent paper using MEG, which measures similar signals as EEG, found support for the involvement of two networks in aesthetic appreciation, and was able to identify that one network was involved early in the response while a second network, potentially corresponding to components of the DMN, was became active in a later time window (750-1000ms; Cela-Conde et al., 2013).

3.5.1.3 Commercially Available EEG Devices. The range of commercially available EEG devices can be grouped into three general classes (see *Appendix, Table A1*). Research grade systems tend to have many electrodes (32-256), cover the entire head using a cap or lattice, and are designed to provide the highest signal quality. They often use “wet” sensors or require the use of skin abrasion and conductive gels to achieve very low impedance connections with the scalp. These systems typically collect data in a raw format, require standalone amplifier systems, and do not permit a subject to move around an environment extensively due to the large number of physical wires coming from the cap.

There also exist a number of “commercial” grade systems that are designed for use in a variety of research and commercial settings, such as psychology research, marketing research, clinical settings, and neurofeedback applications. These systems typically have fewer electrodes (6-24 electrodes) and emphasize ease of use and robustness. This is often achieved by using “dry” sensor technologies that do not require gels or water and by accepting a less stringent impedance threshold as a “good” connection. Many of these systems allow access to raw EEG signals, but also include software for calculating power in frequency bands, along with a variety of real-time constructs such as “engagement” or “excitement” that are based on machine learning algorithms. The general market for these products are “alternative” settings where high quality data is desired, but a larger research grade system may be deemed unacceptable (e.g. difficult patient populations, real-world interactions that involve walking or longer use). Therefore, a major push in these systems is to increase mobility and robustness while not sacrificing signal quality.

The third general class of EEG headsets may be termed “consumer” grade devices. Many of these devices are wireless headsets marketed to the general public as “brain-computer interfaces” (BCI) or neurofeedback devices, and are used in a variety of applications from toys and simple games to personal wellness to marketing research. Many devices contain only a single EEG electrode, though several exist with up to 7 or 14 electrodes. The electrodes tend to be flat, dry, and rest directly on the skin with no abrasion required. The majority of consumer-oriented EEG devices do not provide direct access to EEG data, but instead use EEG signals to derive some signal that is claimed to represent a mental state that is meaningful and potentially controllable by the user (e.g. to control concentration or promote relaxation). Many are accompanied by smartphone apps, and some of the devices do provide readouts of specific frequency bands. In general, many of these devices are more “toys” than useful EEG systems given the impoverished, noisy signal and lack of readout flexibility.

The systems that are likely to be most relevant for use with sensory stimulation augmentation countermeasures are the commercial grade systems, as they provide multichannel signals but emphasize ease of use in a wider range of settings than research grade caps. A current “state of the art” system of this nature is wireless, battery powered, has 6-24 electrodes, and is designed to be comfortable enough for longer wear (e.g. an hour or two) while also providing robust signal and artifact detection. These systems come with software that allows for both raw EEG signal recording as well as real-time measurements of constructs based on machine learning algorithms that may allow for a degree of personalized “tuning” of the measured signal. Note that only a subset of systems have electrodes over the anterior prefrontal cortex (forehead), which may be of particular importance for understanding emotional and aesthetic responses to sensory stimulation. A number of manufacturers are now also looking to offer some degree of integration with other measurement modalities, such as physiological signals, eyetracking (Tobii systems, Google Glass), facial expression tracking or NIRS.

Several specific EEG systems deserve special mention. Wearable Sensing (wearablesensing.com) makes two commercial grade wireless EEG headsets (6 or 24 electrodes) that are dry, wireless, and robust. The sensors are designed to be easily workable through hair, and provide good contact over long periods. Both systems provide access to raw EEG signal, as well as support for extracting real-time frequency band signals and emotional constructs. The 24 electrode system includes a band that goes across the forehead, providing good coverage of the anterior PFC. Emotiv (emotiv.com) makes a 14 electrode EEG headset that gives access to full EEG data, as well as a similar consumer device (EPOC) that does not. Both headsets are dry and wireless, and provide real-time data on emotional states (see Aspinall et al., 2013) above), a limited set of facial expressions, and frequency bands. Neither system, however, has an electrode over the anterior PFC. Within the research grade products, BrainProducts actiCAP products (brainproducts.com) are notable in that they contain 16 electrodes integrated into a cap that can also be used with fNIRS systems. In the consumer grade product class, the InteraXon by Muse (choosemuse.com) is notable for its specific marketing as a stress-calming device relying on neurofeedback training. It has 7 electrodes, putting it at the upper end for a consumer-oriented device.

3.5.2 Functional Near-Infrared Spectroscopy (fNIRS). Functional near-infrared spectroscopy (fNIRS) is a portable brain imaging technology that is non-invasive and relatively inexpensive. fNIRS is based on the same signal as fMRI. However, rather than measuring changes in a magnetic field as a result of blood oxygenation, fNIRS devices are worn directly on the scalp and use measurements of scattered light through the skull to infer brain activity from changes in the concentration of oxygen in the blood.

Given the slow timecourse of the signal being measured (peak in signal 4-6 sec post onset), experimental methodologies for fNIRS are similar to those for BOLD fMRI: block designs, event-related averaging or deconvolution and correlation over time. This may make fNIRS less useful for “real-time” assessments and require more trial averaging, especially given the lower signal-to-noise ratio of fNIRS compared to fMRI (Cui, Bray, Bryant, Glover, & Reiss, 2011).

Within the context of sensory stimulation augmentation, fNIRS may prove to be potentially useful for measuring engagement with stimuli over the time range several seconds to minutes, and for assessments of emotional and aesthetic responses to a session of sensory stimulation. In addition fNIRS could also be useful for assessments of longer-term changes in systems supporting mood, coping, and executive functioning.

3.5.2.1 fNIRS and Affective Responses to Visual Stimuli. There are a few studies that have investigated the use of fNIRS over the prefrontal cortex to measure positive emotional responses to various stimuli. Hosseini et al. (2011) showed five subjects photographs of scenery, clothes, cars, food and animals while collecting fNIRS over anterior frontal cortex using a Hitachi continuous-wave system with 16 photodetectors and 17 light emitters (52 total channels). Using a classification approach, they found that “attractive” vs “other” (neutral or negative) images could be correctly identified from the fNIRS signal for an average of 72.9% of the trials, and that an anterior medial frontal region was most informative for this classification (though it should be noted that it is unclear whether the decoding ability is related to pleasantness *per se* or to the subject’s subsequent decision).

Kreplin and Fairclough (2013) used a Biopac Imager1000 16-probe NIRS system over the medial prefrontal cortex and found enhancement of medial anterior (rostral) PFC signal during the viewing of visual art that induced positive emotions (compared with those that provoked negative emotions), regardless of whether they were asked to emotionally introspect or perform a visual inspection task (e.g. “spot the difference”).

Finally, Sakamoto, Asahara, Sakashita, Yamashita, and Okada (2012) recorded NIRS from two electrodes placed on the left and right sides of participants’ foreheads while watching 3D video content on a high definition plasma television, including a recorded concert, scenery, an action/horror film, and a drama. They reported that NIRS activity was a useful index for evaluating emotional states of “stress-relaxed,” “comfortable-uncomfortable,” and “like-dislike,” and were related to physiological (brain waves, blink rate, heart rate, sympathetic nerve activity) and psychological (via questionnaires and interviews) indices.

3.5.2.2 Commercially Available fNIRS Devices. Given the relative recency of the emergence of fNIRS as a technique for measuring brain activity, the technology is shifting rapidly, and a number of technical challenges are still being addressed. Although there are several methods for performing fNIRS spectroscopy, almost all commercially available products use the “continuous wave” method, in which the light sources emit light of two or more constant frequencies and fixed amplitude (see *Appendix, Table A2*). This allows for a computation of the relative concentration of both oxy- and deoxy-hemoglobin. “Frequency domain” fNIRS allows for absolute measurements of oxy- and deoxy-hemoglobin concentrations, but are much more expensive and less portable than continuous wave systems on account of their technical complexity.

Different fNIRS systems rely on emitters with slightly different frequencies of light, generally in the 650 – 900nm range, and have anywhere between one to sixteen emitters. The light emitted from these sources on the scalp penetrates the skull, and is absorbed or reflected in a manner that is sensitive to hemoglobin concentrations in the capillary bed of the cortex. The reflected light is then detected by a set of sensors that are also on the surface of the scalp, with different devices having between two and thirty-two detectors.

Given the difficulty of measuring fNIRS through hair, a number of fNIRS devices focus on coverage of the forehead, either using individual sensors or a headband. The fNIR 1000, made by fNIR Devices (www.fnirdevices.com/fnirimager1000.htm) and also marketed by BioPac, combines four light emitters and ten detectors at two different wavelengths to measure signal in 16 channels covering most of the forehead. Devices with fewer channels have been developed for a variety of applications, such as two channel systems for monitoring brain oxygenation during surgeries. Dr. Strangman's group at MGH has been working on optimizing a system (NINscan) with similar characteristics for ambulatory applications and spaceflight that uses time-division multiplexing to measure 8 channels. This system is powered by rechargeable Li-ion batteries and weighs less than 500 grams, making it very portable, and the group is working on developing a whole-head system with similar characteristics.

Despite the difficulty with the collection of NIRS signal through hair, there do exist several fNIRS devices that use more emitters and detectors with a cap to cover a greater surface area of the scalp. The ETG 4000 system made by Hitachi (www.hitachi-medical-systems.eu/products-and-services/optical-topography) utilizes sets of probes that can be mounted in holders or in a cap to cover two separate areas, such as left and right motor cortex, or left and right prefrontal cortex. The NIRSport 88 (NIRX; www.nirx.net/imagers/nirsport) is a full-head cap similar to an EEG cap that can have eight or sixteen light sources and 8 or sixteen detectors, which depending on the layout can yield up to 64 data channels. This system is advertised as suitable for some portable applications.

MRRA (www.mrrainc.com/products.php?product=Product-3) has attempted to circumvent the problems of measuring fNIRS through hair by creating a "brush" optode (optical electrode) with fibers that can penetrate through hair to collect the scattered light signal at the surface of the scalp. Tests show comparable results to regular optodes on bald subjects and similar signal levels for individuals with dark hair, whereas conventional optodes show almost complete signal loss with dark hair (Khan et al., 2012).

NIRSOptix (www.nirsoptix.com/CW6.php) makes a system that is notable in that it uses laser light rather than LEDs. By using frequency modulation for each laser source and demodulation at the detectors, they claim that all 32 detectors can measure signal from all 32 emitters, producing up to 1024 raw measurements, giving higher resolution. The hardware needed for this system, however, is quite bulky.

fNIRS is limited in several important ways. First, the spatial precision of current systems, while perhaps better than EEG, is still rather low due to the scattering of light through the skull, and the technology is not suitable for fully three-dimensional mapping. In addition, while the measurement rate is much better than fMRI (25Hz to 200Hz), the signal is still limited by the sluggishness of the BOLD response, which is on the order of seconds. In addition, the light absorption of fNIRS sensors may change due to perspiration, though this tends to stabilize upon sensor saturation. Motion can also be an issue, and it has been suggested that ambulatory systems be coupled with accelerometers and adaptive filtering of motion artifacts. Finally, ambulatory systems must be designed with power consumption in mind – achieving higher coverage by using more channels will shorten the amount of monitoring time that can be performed on a battery charge. Despite these drawbacks, fNIRS is an extremely promising technology for low-cost, mobile brain monitoring, and will undoubtedly show great improvements over the next few years.

3.6 INDIVIDUAL DIFFERENCES

The goal of this section is to consider a potential approach for developing a personality profile relevant for sensory stimulation. Our suggested approach has two components. The first component is to identify personality traits are relevant for determining whether a potential LDSM candidate can cope with reduced sensory stimulation. In this section, we will outline several frameworks for studying individual differences and highlight factors within those frameworks that are likely relevant for selection of mission candidates who would show resilience in the face of reduced sensory stimulation.

The second component of an individual differences approach is the creation of personalized countermeasure profiles – different individuals like different things, and may need different types of information, and in varying amounts, to meet their sensory stimulation needs. This component will help prioritize storage and bandwidth resources to ensure the availability of sensory experiences that meet individual preferences and needs. Within the field of experimental aesthetics, there is growing sensitivity to the fact that individuals often vary widely in what artworks and music people prefer (e.g. Vessel et al., 2012). By characterizing individual crewmembers' preferences before the beginning of a mission using multi-dimensional scaling and machine learning techniques on behavioral preference data, a personalized profile can be developed for each individual. In Section 4 of this report (Countermeasures), we also explore a few commercially available approaches that could be used as models for personalized media selection. We also outline four basic types of sensory stimulation countermeasures. Future research may be able to identify whether personality traits can be used to predict the degree to which different individuals require different balances of these types of countermeasures (e.g. information foraging vs. restoration).

3.6.1 Big 5 Personality Traits. The Big 5 personality traits refer to five dimensions that psychologists use to define an individual's personality (McCrae & John, 1992). This five-factor model consists of the following domains: Neuroticism, Openness (to experience), Extraversion, Conscientiousness, and Agreeableness. The degree to which an individual expresses these traits – particularly neuroticism, openness, and extraversion – could have a profound impact on the effectiveness of sensory stimulation and augmentation countermeasures.

"Neuroticism" is characterized by a tendency to experience anxiety, anger, and other negative emotions. The trait is associated with subjects who have a reduced tolerance for "aversive stimuli" (Norris, Larsen, & Cacioppo, 2007). Careful consideration must be given to countermeasures aimed at subjects who rate as highly neurotic. Overstimulation, difficult tasks, or invasive physiological measurements could evoke excessively stressful responses.

"Openness" refers to a person's receptiveness to new experiences. It is often associated with intellectual curiosity, inventiveness, imagination, aesthetic proclivity, and appreciation and seeking of novel experiences (Costa & McCrae, 1992). Space exploration certainly attracts curious, adventure-seeking personality types, and open individuals may engage more with countermeasures such as virtual reality, opportunistic science, skillshares and creative pursuits. On the other hand, "closed" individuals have a more conservative approach to experiences, preferring routine to novelty and possessing relatively less interest in art and adventure. Whereas current space missions attract personality types seeking stimulation, the potential monotony of long duration missions may favor those with "closed" personalities. Thus, countermeasures may be more efficacious to open types but less necessary for closed types. The optimal balance of the traits appropriate for LDSMs requires further study.

"Extraversion" reflects one's tendency to find socialization and activity engaging. Often talkative and enthusiastic, extraverts would likely enjoy interactions with crewmembers, and they would thus benefit by group activity countermeasures like skillsharing, mealtimes and celebrations. Introverts are also likely to find benefit from proposed countermeasures, though the salient measures might differ. For instance, introverted crewmembers may show stronger preference for independent meaningful research, virtual reality stimulation, or cultivating plants. The appropriate selection of countermeasures is concomitant with the selection of the crew.

Closely related to openness and extraversion is the non-Big 5 trait of "sensation seeking" (Roberti, 2004). The Sensation Seeking Scale (SSS), for instance, was developed to quantify traits of thrill-seeking, disinhibition, experience-seeking, and susceptibility to boredom (Zuckerman, Eysenck, & Eysenck, 1978). Sensation seekers tend to prefer strong sensory stimulation, giving corresponding countermeasures great utility. However, such individuals may also present a higher risk for LDSM if countermeasures deployed to counter the monotony of transit is not sufficient to prevent risky sensation-seeking behaviors.

3.6.2 Proneness to Boredom. A second framework for developing a personality profile relevant to sensory stimulation is the measurement of whether an individual is prone to boredom. The Boredom Proneness Scale (BPS; Farmer & Sundberg, 1986) is a self-report questionnaire on which a person answers true/false to 28 questions such as "I am often trapped in situations where I have to do meaningless things" ("True" indicates higher susceptibility) and "I find it easy to entertain myself" ("False" indicates higher susceptibility). Similarly, the Boredom Susceptibility Scale (ZBS; Zuckerman, 1979) is a subscale of the Sensation Seeking Scale (SSS, see above) that relies on ten questions that ask observers to choose an answer to a potential scenario. Higher scores on these tests have been associated with neuroticism, experiential avoidance, attentional and motor impulsivity, anxiety, depression, dysphoria, sensitivity to reward and alcohol use (Mercer-Lynn, Flora, Fahlman, & Eastwood, 2013)

Responses on these measures may help identify potential crewmembers that will show greater resilience to reduced sensory stimulation and monotony, and may also be useful in understanding individual's differing stimulation needs, as well as their likelihood to respond to sensory stimulation augmentation.

3.6.3 Positive and Negative Valence Systems

3.6.3.1 NIH Research Domain Criteria. In response to a growing body of evidence that traditional diagnostic categories such as autism, depression, anxiety disorder, and PTSD are failing to fully capture the variety of individual variability in mental function and dysfunction, the National Institute of Mental Health has recently begun an initiative that seeks to develop a *dimensional* understanding of behavior that cuts across traditional diagnostic categories and is linked with the function of neural systems. This Research Domain Criteria (RDoC) approach divides mental function into a set of cognitive and emotional domains such as perception, attention, executive function, positive valence and negative valence, for which there is evidence supporting their correspondence with specific neural systems. Within each of these domains, a number of independent constructs have been proposed (e.g. threat, approach motivation), and researchers are encouraged to link these constructs across multiple levels of analysis, such as behavior, neural circuits, and molecules.

This approach, which is intended to eventually replace the standard diagnostic categories of the American Psychiatric Association (e.g. the DSM-IV; APA, 1994), represents a powerful new framework within which to understand both normal and abnormal variation in individual function. As NASA BHP moves forward with the work of understanding what characteristics would support resilience on long-duration missions, it can likely benefit from aligning its research with the evolving RDoC framework.

With respect to sensory stimulation, the most relevant high-level domains are Cognitive Systems, Positive Valence Systems, and Negative Valence systems. Within the Cognitive systems, perception and attention are the most relevant constructs. As should be clear from Sections 1 and 2 of this report, the largest consequences of reduced sensory stimulation are likely to be mediated by affective and emotional responses. Therefore, most of the constructs of Negative Valence (acute threat, potential threat, sustained threat, loss, frustrative nonreward) and Positive Valence (Approach Motivation, initial responsiveness to reward, sustained responsiveness to reward, reward learning, habit) are likely relevant to sensory stimulation.

3.6.3.2 Measuring Positive and Negative Valence Constructs. Given the relative recency of the RDoC approach, much of the current research on positive and negative valence systems attempts to relate more traditional trait measures of reward responsiveness, anhedonia, dysphoria, anxiety and loss to the RDoC constructs. For example, a variety of measures of depression symptomatology (e.g. BDI and Montgomery-Åsberg Depression Rating Scale [MADRS; Montgomery & Asberg, 1979), anxiety (e.g. STAI and Hamilton Anxiety measure [HAM-A; Hamilton, 1959]), anhedonia (e.g. TEPS, CPAS, SHAPS), and behavioral approach/inhibition (see below) have been related to constructs of positive and negative valence.

As was mentioned in Section 2 and above, dissociations between approach motivation ("wanting") and initial responsiveness to reward ("liking") have been found at both the neural and behavioral levels. One promising future direction for developing personalized sensory stimulation profiles might be to characterize individual function of these two systems, both in terms of their overall responsiveness and in terms of how people differ in what they like or want. This could be done using behavioral rating and keypress tasks.

Several tasks were described in the "State" section that measured aspects of mood congruency and differences in reward responding for anhedonic or dysphoric individuals. Many of these same tasks may be useful for measuring stable trait levels of positive and negative valence function. Notably, Gupta and Kar (2012) found effects for remitted patients who had since recovered from depression, which suggests that their measure may actually reflect more stable trait markers. Specifically, they found that depressed patients, and remitted patients show slower responding than controls when asked to name the colors of negatively-valenced words, which the authors suggest is caused by a bias to process the words, causing interference of color naming (Gupta & Kar, 2012). Depressed and remitted patients were also slower to generate autobiographical memories in response to positive word cues, whereas controls were slower to generate autobiographical memories to negative word cues (Gupta & Kar, 2012).

3.6.4 Behavioral Approach and Inhibition. The Behavioral Approach and Behavioral Inhibition scales (BAS/BIS) are designed to measure the function of systems that mediate approach behaviors toward conditioned rewards and inhibition of approach (or withdrawal) from conditioned punishments (Carver & White, 1994). It is suggested that differences in these systems may explain individual differences in anxiety and impulsivity

(Jorm et al., 1999). The BAS scale is divided into three subscales reflecting reward responsiveness, drive and fun seeking.

3.6.5 Imagery Ability. Individuals differ in the degree of vividity of their mental imagery. There are some claims that high imagers show better performance some tasks, such as recall of color photographs (Marks, 1973) and detection of salient changes across two viewings of an image (Rodway, Gillies, & Shchepman, 2006). It is possible that differences in imagery ability and vividity may impact how an individual responds to reduced sensory stimulation. For example, a high imager may need less exogenous sensory stimulation due to their ability to internally generate rich mental images. However, the converse may also be true. Further research will be needed to explore whether there is any meaningful connection.

Imagery ability has been measured using the Vividness of Visual Imagery Questionnaire (VVIQ; Marks, 1973, 1995). Subjects are given specific scenarios or scenes to imagine, and are asked about the vividness of the mental images. The VVIQ contains 16 questions, and the VVIQ-2 was revised to include twice as many questions. It can be performed with eyes open or eyes closed.

At least some form of imagery ability can also be measured using fMRI. Individual differences in vividity of mental imagery have been found to be correlated with responses in early visual cortex to on a Stroop task for color/word interference (Cui, Jeter, Yang, Montague, & Eagleman, 2007).

3.7 SUMMARY

- There is a need to develop metrics for the acute and chronic effects of sensory stimulation levels and for establishing countermeasure effectiveness.
- A number of models exist for quantifying low-level properties of a variety of stimuli.
- Very few models exist for quantifying higher-level properties of stimuli, such as the presence of objects or scene gist. Modeling affective responses to stimuli would require dynamic models that capture the current state of a person's knowledge and understanding.
- Theories of information such as algorithmic information theory and integrated information theory, may capture central aspects of the mathematics that would be necessary for such models.
- Acute stimulation levels and real-time engagement are reflected by perceptual intensity, arousal, attention and affective constructs (curiosity, surprise, liking, wanting, beauty, etc.). There has been some progress made in measuring these constructs using a variety of self-report, behavioral, physiological and brain-imaging measures.

- Chronic or cumulative effects of sensory stimulation levels relate to constructs such as perceptual thresholds, attentional capacity, stress, coping, mood and well-being. Many of these constructs can also be measured using self-report methods, computer-based psychophysical and cognitive tasks, psychophysiology and brain imaging.

Behavioral and Self-Report Measures

- A variety of psychophysical and cognitive methods exist for quantifying aspects of responses to stimuli.
- A large number of questionnaires have been developed for measuring mental states. Although some of these measures have been shown to have both internally consistency and construct validity, a large number of questionnaires have unknown construct validity and questionable reliability.
- Several laboratory-based tasks have been developed for measuring sensory thresholds, cognitive function and affective responding.

Measurement of Objective Physiological Correlates

- Psychophysiological measures have promise as objective markers of internal emotional states. Electromyography has been shown to correlate with affective valence and arousal, but require electrodes to be attached to the face. Less invasive measures like heart rate acceleration and skin conductance, also show some correlation with valence and arousal (respectively) and can be measured using commercially available devices worn on the wrist or arm.
- Video cameras can be used for tracking eye movements, pupil dilation and facial expressions. These measures can be collected remotely (i.e. by a camera mounted at a workstation) and show promise in measuring interest, attention, engagement, anxiety, arousal, and a host of facially expressed emotions (e.g. anger, joy, sadness, surprise). However, the robustness of these measures is heavily dependent on the relative position of the person to the camera, lighting, and calibration.
- Electroencephalography measures electrical potentials on the scalp that are generated by the brain. The development of increasingly mobile wireless EEG headsets and of real-time analysis methods has lead to their increasing use in a variety of ambulatory contexts, such as product and website design and research on exploration in real-world contexts. Although the ability of EEG to provide high SNR real-time measures remains unclear, EEG represents a potential avenue for measuring real-time measures of engagement, directed attention, surprise, frustration and cognitive control. A variety of commercially available EEG devices are available that strike a balance between ease of use and data quality.
- Functional near-infrared spectroscopy (fNIRS) measures the same blood-oxygenation dependent signal that is used in fMRI by shining light through the skull and measuring the properties of the subsequently scattered light. Although they are

relatively new, fNIRS devices are highly portable and appear capable of measuring correlates of affective signals from the prefrontal cortex. Although its ability to measure through hair is limited and fNIRS has a low signal-to-noise ratio, it is a technology that is undergoing rapid development, and represents an attractive option for quantifying subjective states of pleasure, engagement and stress.

Individual Differences

- Measuring differences in personality will help formulate information about personality profiles that are likely to show resilience in the face of reduced sensory stimulation. In addition, individual difference measures can be used to create personalized countermeasure profiles. In addition to the suite of measures mentioned previously, a variety of self-report measures exist that claim to measure relevant constructs of personality, such as extraversion, neuroticism, proneness to boredom and imagery ability. The NIH Research Domain Criteria (RDoC) represent an effort to create a dimensional replacement for the diagnostic category approach currently used in psychiatry, and will be an important component of future work on understanding individual differences.

SECTION 4: COUNTERMEASURE EVALUATION

Framing Question: What set of countermeasures would best meet the needs of sensory stimulation augmentation and the constraints imposed on the mission?

There remains much to learn about how the sensory properties of ICE environments affect performance, mood and well-being, and what are the best approaches for counteracting the potential negative affects of reduced sensory stimulation and monotony. However, the background literature and theory provided in sections 1 and 2 of this report provide the outlines of a useful general framework for evaluating potential countermeasures and for organizing future research. In this section, we outline this framework, put forth recommendations for a set of parameters and benchmarks by which potential countermeasures can be evaluated, and consider the degree to which existing or developing technologies may meet these needs.

4.1 EVALUATING COUNTERMEASURES

A major goal of NASA's BHP element is to build and maintain resilience – the ability to perform in the presence of stressors, and to recover from them. Within this context, sensory stimulation fulfills multiple needs. By understanding and measuring these different requirements, countermeasures can be designed that target specific needs.

1) <u>Information foraging</u>: Sensory stimulation engages the human information foraging drive, which is related to brain systems that mediate understanding (sense-making), learning, exploration and sensation seeking. Adequate stimulation of a high degree of novelty and interpretability prevents boredom and subsequent stress.

2) <u>Relaxation and restoration</u>: Certain forms of sensory stimulation allow for recovery from stress and restoration of attentional resources.

3) <u>Therapeutic release</u>: It is sometimes necessary for an individual to engage in active processing techniques to "work through" an emotional response to an event, with the goal of regulating the emotional response and modifying future behavior. Although less common, sensory stimulation can play a role in some of these techniques, such as art- or movement-based therapies.

4) <u>Homeostatic maintenance</u>: Although most aspects of sensory systems in adults are largely immune to changes in the low-level statistics of the environment, there do exist some systems where long-term sensory or perceptual deprivation may lead to "retuning"

or loss of sensitivity. Certain forms of sensory stimulation and sensory filtering may be important for protecting against such changes.

Table 4.1. Sensory stimulation fulfills a variety of needs. These needs have different relationships to stress and coping.

NEED	Relationship to STRESS	Example Countermeasures
Homeostatic Maintenance	Disruption of homeostasis leads to degradation in performance, increasing stress and decreasing coping	• Noise control • Exercise with simulation of gravity
Information Foraging	Lack of activation in higher regions of perceptual analysis pathways leads to an unmet drive state, increasing stress	• Meaningful work • Learning/education • Media consumption • Windows / Displays • Virtual Reality • "Skillshares"
Restoration / Relaxation	Restoration of resources and passive stress release increase coping	• Nature (real / virtual) • Habitat design • Music • Mindfulness • Creative pursuits • Restorative touch
Active Release	Problem-oriented coping and active stress release	• Exercise • Play • Celebrations • Therapy

There are a host of other considerations that must also be evaluated in order to determine the potential usefulness of countermeasures. The effectiveness of a countermeasure is likely to be modulated by its degree of interactivity, meaningfulness, and personal relevance. The availability of a diversity of different potential countermeasures, with different approaches and modalities, will aid in preventing a crewmember from effectively habituating to any one countermeasure, as well as increase the likelihood that a specific individual crewmember will respond positively to one or more countermeasures. Diversity in the timescale of operation is also important – different effects, such as the perceptual versus emotional consequences of sensory stimulation levels, occur across multiple timescales, and both measurement techniques and countermeasure design should be sensitive to the timescale of the targeted process.

Countermeasures must also be considered within the larger context of the mission. While cost is clearly a factor, the more difficult constraints to satisfy are those imposed by the capsule design: mass, size, volume, and placement within the space. Developing measures of the impact of specific countermeasures is of critical importance for conducting this type of cost-benefit analysis. Finally, the likelihood of use by the crew (e.g. low annoyance) is another critical factor in evaluating the actual (rather than hypothetical) benefit of a proposed countermeasure.

In addition to classification by need, it is also important to classify sensory stimulation countermeasures in terms of sensory domain, whether they serve a perceptual or social purpose, whether they are passive or active, by their degree of invasiveness, and by whether they are relatively low- or high-tech. With the possible exception of invasiveness and technology requirements, which could both be perceived as costs, BHP should strive to achieve a diverse repertoire of countermeasures across these classifications.

4.2 INFORMATION FORAGING

Information foraging countermeasures are designed for active exploration, engagement of attention and curiosity, and learning. They deliver "aha" moments. A successful suite of information foraging countermeasures will prevent boredom and the subsequent negative consequences in affect, mood and well-being. Information foraging countermeasures support resilience by giving purpose and supporting agency.

Key factors to consider for information foraging countermeasures are novelty, interpretability, meaning and storyline, and personal relevance (see *Section 2.3*). Active exploration is also important (agency), and understanding a person's abilities and expertise are critical for identifying what domains a person will find engaging and can successfully explore. Intellectual challenges, and the ability to solve such challenges (e.g. "getting it"), play a key role in the pleasure and benefits of information foraging.

4.2.1 Meaningful Work. Although the question of how to structure an astronaut's work is a very broad concern that extends significantly beyond the scope of sensory stimulation augmentation, the importance of engaging crew in work that they find personally meaningful cannot be understated. As should be clear from the theoretical review presented in Section 2, it is difficult to draw a clear line between pure sensation, higher cognitive functions (recognition, extraction of meaning) and affective and motivational considerations. Activities that engage higher-order regions of perceptual pathways, trigger associative meaning and lead to "aha" moments will be more enjoyed and have positive effects on mood. This fits with the general notion that the best jobs are those that engage one's curiosities and talents. Meaningful work satisfies the need for information foraging, and is a critical component of helping to maintain resilience in an environment lacking in sensory variety and contact with the outside world.

How can work be made more meaningful on long-duration missions? First, astronauts can be given a greater degree of control over their work during both the transit and surface phases of the mission. This will involve granting crewmembers more up-front input on what science will be done and greater autonomy over moment-to-moment decision-making. Crewmember selection could even seek to incorporate individuals that could function as principal investigators on self-designed experiments. Peldszus et al. (2014) noted in their review of diaries of space missions that personal or voluntary science projects were extremely highly valued. Second, the crew should have access to the tools and information they need to make the most of the unique nature of their circumstances. An example of such "opportunistic" science would be to take advantage of the crafts' position in interplanetary space to perform measurements of deep space, using appropriate instruments for reading and imaging regions of the electromagnetic spectrum (visible, microwave, radio wave, background radiation, etc.). Giving crewmembers access to information databases about objects in the solar system objects (planets, asteroids, the sun, moons, etc.) and beyond would put crewmembers in a better position to engage in opportunistic experimentation that their flight trajectory may be uniquely situated to answer.

Adding an educational component to crewmembers' work could also add meaning and significance. For example, several of the crewmembers could participate in the preparation of educational video and multimedia segments about their mission and the science being performed. Similar projects by past and current astronauts, and of non-space voyages (e.g. the 1980's Voyage of the Mimi production), have been very successful.

There will undoubtedly be a significant amount of work for any LDSM crew that is extremely necessary, but mundane and potentially frustrating. While this cannot be avoided, increasing the likelihood that crewmembers can choose to engage in work they find personally meaningful and rewarding will have tremendous positive impact not only on productivity and work quality (Chandler & Kapelner, 2013) but also on mood and well-being.

4.2.2 Learning and Educational Pursuits. Information foraging needs can also be met by opportunities for learning. However, in line with the recommendations for meaningful work, astronauts are not likely to engage with in-depth educational materials (e.g. remote coursework) that are not relevant to the mission in some way. While it may be relatively low-cost to include video or computer-based educational material available on a variety of subjects of interest to the crew, the bigger impact is likely to be scientific and analytical information that are relevant to ongoing scientific projects.

A second potential model for how LDSM crew could engage in meaningful learning experiences is the "skillshare" model. In this scenario, astronauts would be given the opportunity during pre-flight training to learn about (or work on) a skill that they have had an interest in, such as acrobatics, sewing, art, magic, coding, building integrated circuits, HAM radio operation, playing an instrument, etc. During the mission, the crew could each then lead a series of sessions where they share aspects of that skill with other interested crewmembers. Skillshare sessions help provide a sense of community and play, while engaging individuals in something that is both challenging and rewarding.

4.2.3 Media Consumption. It is clear that any LDSM mission will include a variety of media for consumption by the crew. Beyond the basic recommendations that a wide variety of types of media and content be provided, there are several additional factors that can help ensure that media consumption adequately addresses astronauts' information foraging needs.

The availability of media that maintains storyline continuity is important. Series of shows, books, or movies that create a sophisticated world and explore within that world allow a person to delve deep – the presence of story arcs that have different levels of complexity and timescales of resolution help establish a greater sense of personal history and relevance.

The amount of media that is available today is staggering. Yet storage of this media is not necessarily the biggest issue with access to this media – the bigger problem is finding out what things a person might enjoy. The problem of *too much* choice has become ubiquitous in today's media saturated world. The general form of a solution to this problem could be considered a problem of curation that seeks to answer the question "what will I like?", either based on someone's expert opinions, or on the basis of my past history. A great many people today have largely foregone collections of large numbers of albums or movies in favor of services that curate media for them, such as Pandora, Netflix, or Artsy (a curation engine for visual art). At their core, these services a) code media on a large number of features ("genes" in the parlance of Pandora) and then b) build models of a person's preferences based on their past choices and their similarity to other users. This approach allows for predictions to be made in a meaningful feature space, such as genre (e.g. romantic comedy, trip hop), formal features (speed of video cuts, musical tempo, artistic medium) and even specific content (e.g. George Clooney, TV shows that take place in San Francisco, songs written about dogs and trucks, paintings of the Virgin Mary). The availability of such services, which form an important aspect of a *personalized* approach to sensory stimulation, allows individuals to find what they know, but also discover new content with fewer "misses."

The implementation of both of these suggestions will depend on the bandwidth of electronic communication channels between Earth and the craft. In a situation where little or no bandwidth could be dedicated for entertainment media, media curation services like those described would still be useful for exploration of on-board media. However, if it will be possible for new media to be uploaded from Earth, the use of machine learning techniques to guide optimal media selection represents an excellent strategy for prioritizing the use of limited network bandwidth. It also represents a key way in which LDSM crew, cut off from real-time communication with their friends and family, can feel as if they are still a part of the shared cultural understanding and progression.

Although the maximum communication delay of up to 40 minutes round-trip is not likely to present any issue with respect to recommendations for movies, there is a gap in our understanding of how information foraging operates under a time delay. The problem can be understood as how to predict what someone will want at some later time T_1, based on their choices or expressed preferences at an earlier time T_0. Research into this question could be relevant for media on shorter timescales, such as music or news.

4.2.4 Communication. Communication with family and friends, along with the reception of news and events from Earth, are forms of sensory stimulation that have been very high priorities for members of previous mission crews. Communication with other people, and about events taking place on Earth, clearly satisfy an information foraging need – other people are primary entities about which humans know a lot and get pleasure from learning more about. In addition, communication clearly serves a need for connection and community, and it can serve a therapeutic function as well. Although the presence of a communication delay will reduce the forms of communication that are available, they will no doubt continue to play a central role for LDSM.

To reduce the negative effects of communication delay or signal disruption, several recommendations should be considered. First, extensive preflight training scenarios should provide adequate exposure to such potential issues. Next, attempts should be made to preprogram automated mission control command responses for when astronauts encounter particularly time-sensitive challenges that require ground support. For personal communication, User Interface experts should work to design interfaces suited for slow communication rates: innovations inspired by email clients, rather than instant messaging services. Consideration should be given to the ideal size and format (e.g. text, video) of correspondences necessary and sufficient to minimize the stressors of delayed contact. Lastly, Delay- and Disruption-Tolerant Networks of satellites serving as communication servers will allow for high fidelity signal transfer, even when large bodies occlude the direct Earth to Mars trajectory (e.g. www.technologyreview.com/news/411092/a-better-network-for-outer-space)

4.2.5 Real and "Virtual" Windows. A major decision facing LDSM designers is whether crafts need to have windows, since the materials needed to construct a window that is strong enough to not be a point of structural weakness and screens out harmful radiation are very heavy. On the one hand, windows aboard the ISS and other space missions to date have been highly valued, often providing a primary pastime for crewmembers and being a major gathering spot. On the other hand, the concern has been raised that the Earth will not be a prominent feature of the view out a window, and that watching it recede into a small dot may even have negative psychological consequences. According to this view, the positive benefits of a real window, along with its potential harm, do not justify the engineering, space, and mass costs of having real windows. An attractive alternative would be to invest in realistic "virtual" window technology capable of displaying not only what is outside the spacecraft but of any number of other images or scenes.

4.2.5.1 The Benefits of a Real Window. Although large field-of-view, high fidelity display devices are likely to play a key role in countermeasures for both information foraging and restoration (see below), in our view the arguments in favor of having at least one actual window are extremely compelling, and the concerns raised above miss the mark in several important ways.

It is not the case that the view out a window that is not dominated by the earth is empty, uninteresting and unchanging. Quite the opposite – it will be a view of the stars that no human has ever seen before. Don Petit, in an interview on his passion for astrophotography (http://science.nasa.gov/science-news/science-at-nasa/2003/24mar_noseprints), made it quite clear that while he immensely enjoyed photographing the earth, he also very much enjoyed photographing features outside of the solar system from this novel vantage point. Being away from the Earth's atmosphere will present a unique opportunity for observing and photographing distant stars and galaxies by the crew in ways that are likely to be much more personally satisfying than relying on externally mounted cameras. Even the receding Earth, rather than being a source of dismay, could turn out to be a source of novel information as astronauts observe it from a vantage point never before seen (such as the first view of a lunar transit from beyond the moon's orbit). Likewise, the changing view of other objects in the solar system, such the ever-growing size of Mars, would likely be an endless source of fascination.

The ability to directly observe the sun, and feel direct sunlight, is another key factor that strongly supports having an actual window. Even at the Martian orbit, the sun's apparent diameter is still two-thirds its apparent diameter as perceived from Earth, which may serve as a potent visual reminder that "home" is not that far away. The brightness of the sun is approximately 44% of its brightness at Earth (quest.arc.nasa.gov/mars/ask/atmosphere/Brightness_of_daylight_on_Mars.txt), which is still much more than indoor environments, and exposure, if properly timed, could continue to play an important role in maintaining circadian rhythms (Zeitzer, Dijk, Kronauer, Brown, & Czeisler, 2000).

In interviews with astronauts and support staff, it is not uncommon for support staff (designers, psychologists) to express the view that windows may not be worth the cost. Astronauts, on the other hand, repeatedly and emphatically defend the importance of having real windows during spaceflight, even when asked to factor in the unique nature and length of LDSM. One astronaut even went so far as to say that he would refuse to be a part of any LDSM on a craft that did not have a real window (personal communication).

There are a number of practical constraints to consider for the design of a window. In her book on spacecraft architecture, Sandra Häuplik-Meusburger (2011) recommends windows with multiple viewpoints, enough space for someone to pass by, and the ability to be in multiple body positions. Although it is likely that window the size of the cupola on the ISS is not possible (largest window 31" diameter), a window of that is approximately 12" in diameter may be sufficient to allow for multiple viewpoints and body positions. Windows would likely need one or more polarizing filters to eliminate reflections off the spacecraft surface and should be able to be closed completely. The use of real windows in a surface habitat, while requiring many of the same considerations, will be more straightforward and is highly recommended.

4.2.5.2 Large Screen Technology and Virtual Windows. Given both the constraints on the size of any real window on a LDSM craft and the need to provide other visually diverse, immersive experiences, visual display devices are likely to play a critical role in meeting astronauts' sensory stimulation needs. The use of visual displays for specific work tasks (e.g. interfacing with specific instruments, data analysis, writing), media consumption and communication likely would not demand technologies that are not already in widespread consumer use, such as a typical LCD screen, laptop screen, or tablet screen. However, sensory stimulation countermeasures for long duration isolation and confinement must meet an individual's needs for information foraging and restoration, and small field-of-view devices are likely to fall short in this respect. As will be discussed in more detail in Section 4.3, the degree of immersiveness of a visual experience is likely a key factor for achieving restorative effects. Additionally, some forms of media consumption likely provide a much greater impact with large field-of-view devices (e.g. watching movies), and the positive benefits of interactive or exploratory forms of information foraging (e.g. gaming, virtual worlds) may depend critically on the degree of immersiveness, or "presence." Here, we will outline existing large-screen technologies, and in Section 4.2.6.1, we will discuss head-mounted displays.

One of the major benefits of having a large screen display in a confined capsule environment is the potential for many different uses. Not only can a large display be used for watching video or movies, it can also be used to for showing static photography or "background" video of natural and non-natural environments, in conjunction with input devices (see *Section 4.3.2.2*) as part of an interactive system for simulated environments (natural, manmade, fantasy) and training exercises, and if needed, as a data or software interface. Unlike head mounted displays, large screen displays can be on for long periods in the background, can be viewed by multiple people at one time, and don't require the sophisticated optics, head movement tracking and low persistence needed for VR headsets, making them easier to program. However, they are much more limited in the degree of immersiveness and interactivity that can be achieved (including limitations on 3D rendering), and depending on the device, they may take up a lot of surface space.

There are two primary classes of large displays in commercial use today – various forms of television screens and projectors (see *Appendix, Table A3*). Below, we will review several of the current and developing display technologies that may be particularly well suited for use in an LDSM capsule environment. We will not discuss display technologies that utilize (internal) rear projection, such as CRT, LCD or DLP rear projection systems, since their weight and depth, despite significant improvements, are still significantly greater than flat-screen technologies with equivalent (or better) resolution and comparable price. In addition, plasma screens, which have had a strong presence in the consumer television market for the past 10 years, are also being eclipsed by developments in LCD and LED technologies, and will not be discussed. Plasma TVs tended to have better image quality for the price, but consumed much more power.

Characterizing Displays. Size and resolution are primary ways in which displays can vary. Existing commercial devices can be found at almost any desired size (handhelds to projectors to billboards), and the rapid reduction in the size and power consumption of the technology for producing individual pixels means that high resolution can be achieved for even very large devices (e.g. 68 pixels-per-inch, or PPI, for a 65" screen). Note that although computer monitors regularly surpass 200 PPI, and many smartphone devices regularly exceed 300 PPI, such high pixel densities are not necessary for a device that is intended to be viewed from a viewing distance of one meter or more. Current video formats for consumer televisions include high-definition (HD, 1280x720 and 1920x1080, e.g. "1080p") and the new "ultra high-definition" standards, 4K UHD (3840x2160) and 8K UHD (7680x4320).

In addition to the size and resolution, image quality on a display device is strongly related to brightness, contrast ratio, color gamut, and black level, which are all properties that depend on the range of luminance that can be achieved by each color channel. The brighter the screen, the greater ability for it to be used in bright ambient light (e.g. sunlight), while black level refers to the luminance when the pixels are "off". The larger the range between the darkest black and lightest white, the greater the contrast that can be achieved, which is extremely important for being able to mimic the number of distinct light levels typically found in a real scene on a display screen. Color gamut refers to the range of colors that can be produced on a display, and is a function of the range and frequency characteristics of individual color channels and how they are combined (typically red, green and blue). For example, it is generally easier to produce bright green light than it is to produce blue light of an equivalent subjective brightness, which can limit the range of colors produced by a technology.

Several other factors are also important to consider. A large-screen display that is to be used in an area where it may be viewed by multiple people or from a non-static position needs to have a decent viewing angle, so that the image does not fade or distort when viewed from directions other than head-on. If a display is to be used for non-static displays, such as fast-moving video or gaming applications, then it is also critical that it have a high framerate and response time. Finally, energy consumption is another major driver of display technology.

LCD. The majority of consumer display devices are LCD screens (liquid crystal display). The basic technology behind LCD screens is a lattice of liquid crystal pixels whose structure changes when a current is passed through the liquid crystal. Polarized light, which consists of a photon stream that has been filtered to contain only photons with oscillations in a single plane, is either unchanged or rotated by the crystal, and this then determines whether it will pass through (or be blocked by) a second polarizing filter. Although past versions of LCD screens have consistently had issues with producing high-contrast images that are viewable from a range of viewing angles, several rounds of technology development have resulted in devices that have sufficient brightness, contrast, and refresh rate to be competitive with other technologies that are more bulky and use more energy. As LCDs do not produce their own light, most devices are backlit by a separate light source, with LEDs being the primary light source in use in most devices.

In general, LED-backlit LCD displays are excellent choices for computer monitors and viewing of static images given their low power consumption and light weight, but are less than ideal for gaming environments or use in high ambient light due to their relatively slow response time, refresh rate and low contrast and brightness levels. A large number of companies manufacture LED-backlit LCD displays, with Samsung and LG being particularly notable for their ability to incorporate cutting-edge improvements into current consumer electronics. Samsung currently offers large-display LED-backlit LCD screens with both HD and 4K UHD resolutions in sizes ranging from 55" to 85" along the diagonal, weighing from approximately 30 lbs. to as much as 130lbs. LG offers a similar range of devices, though its screens tend to be heavier. Contrast and black level for typical LED-backlit displays are poorer than for plasma screens since they only have LED's along the edge. There are some screens that have local LED's, allowing for a part of the screen to go completely dark and increase contrast ratio. However, these models are much more expensive. Current state-of-the-art LCD screens have up to 240Hz refresh rates to combat motion blur, and have viewing angles of up to 36° in each direction (compared to 72° in each direction for plasma screens).

OLED. Development of new display devices is quickly coming to be dominated by OLED technology (organic light emitting diode). Unlike LCD screens, OLED's do emit their own light, eliminating the need for a backlight, and dramatically improving brightness, dark level, contrast and color gamut. In addition, OLED screens consume even less power than LED LCD screens, but offer better picture quality than many previous technologies, particularly in terms of speed (sub-millisecond framerates). Although most OLED devices are 1080p, UHD OLED devices are beginning to appear on the market, and it is likely that several manufacturers will have offerings in the next year, with Samsung and LG again being the leaders (e.g. LG's 77" UHD OLED).

Two aspects of OLED technology make it particularly exciting for applications in LDSM. The first is that OLED can be printed on extremely thin, flexible materials. LG recently unveiled an 18" screen that can be rolled down to a 3" tube, which could allow for an ideal combination of the stowage capacity of a projector system with the ease of use of a traditional screen (e.g. no blocking of the projector, ability to be used in high ambient light). The second advance is the development of increasingly transparent OLED screens. While largely still in the development phase, this technology would allow the incorporation of video screens into transparent surfaces such as windows, glass panels, handheld devices and eyeglasses for augmented reality.

There are several limitations to current OLED technology. Blue OLEDs currently have efficiency and lifespan issues, requiring them to be driven at a higher output and resulting in faster degradation of the blue channel. The materials can also degrade and are susceptible to damage, resulting in pixel loss. And while power consumption is generally less than that of LCDs, white images can require up to 3 times the power consumption. Finally, the cost of producing OLED technology is still very high compared to LCD. AMOLED devices, which are less expensive to produce, are not yet scalable to larger screen sizes.

Both LCD and OLED technologies can be used to make “3D” displays using either differential light polarization or shuttering. These technologies require a user to wear a pair of glasses that filter different images to the two eyes. There are also displays that project two different images to the two eyes that do not require glasses, but only produce a 3D image when viewed from straight-on.

Using a similar technology, Samsung’s “Multi-view” TV function could be considered as a potential solution for allowing multiple people in one space to be using the screen for different purpose, though this necessitates that viewers wear different glasses (money.cnn.com/gallery/technology/innovation/2014/07/10/samsung-gadgets/index.html).

Projectors. As opposed to large display screens, projectors do not require that a fixed device serve as a viewing surface, making them extremely practical from a stowage and space usage perspective while providing extremely large display sizes. On the other hand, the requirement for an unobstructed line of projection and minimum throw distance of several meters makes their use in a confined space problematic. In addition, despite increasing light output in recent models, most projector systems require a darkened room for best viewing. Although it is possible that some of these issues could be mitigated with careful placement and improvements in brightness, it is likely that the use of projectors in a confined capsule environment would be limited to social activities such as movie watching, when the majority of a crew would take part and the need to move through the projection beam would be limited. However, the rapid development of flexible OLED technology is likely to make even this use of conventional light projectors unlikely.

There is, however, one notable advance in projector technology that could overcome some of these issues. LG’s HECTO Laser TV uses laser light passed through multiple lenses and reflected upward from a projector unit onto a specially designed screen that reflects the light toward the viewer and filters out incident light. As a result, this 100” projector screen can be used in full daylight, and the projector unit fits entirely within two feet of the display surface. The LG HECTO TV has a large viewing angle (178°, 89° per side), excellent contrast ratio (1,000,000:1) and a max power consumption of 400W.

Other Developing Technologies. Several other display technologies have seen some degree of development over the past few years, but none of them appear to have any specific benefits that would make them a likely choice for long-duration spaceflight capsule design. Laser phosphor displays (LPD), which act on a similar principle as a cathode ray tube but using a laser light rather than electron beams, are currently almost inches deep, which does not make them competitive in this environment. Their current use is primarily in large video walls in stores. Surface-conduction electron-emitter display (SED) and field emission display (FED) are two similar technologies that, rather than using one single large cathode ray tube with a single electron source, stimulate an array of phosphor elements using a full matrix array of electron guns. They tend to be the same general size as LCD screens, but are brighter and have a lower energy usage. However, no companies are actively developing these technologies, save for one company, AU Optronics, who is working on FED displays.

Many of these commercially available displays have some degree of integration with devices for input and interaction, such as motion and position sensing, voice commands, and rudimentary hand gesture control or eye-movement control.

Recommendations. Including some form of large field-of-view, non-head mounted display would provide a platform for a wide variety of information foraging and restorative countermeasures, in addition to any potential head-mounted VR. Display systems for either media consumption, virtual windows, or gaming/VR should be separated from primary monitors used for work, and placed in personal space or social relaxation space. Otherwise, it is possible that non-work related uses of a screen in a workspace will not be prioritized because of social pressures, and its use may also not provide enough mental distance between work and relaxation. Priority should be placed on size, resolution, large contrast and color range, along with potential for multiple uses and for stowage. 3D may be a feature that is less important, especially if head-mounted technology is also considered. However, these two technologies may serve quite different purposes, with large-screens being more useful for social events and background environmental display, while VR technology may be more useful for interactive countermeasures.

4.2.6 Virtual Reality and Gaming. For many people, the thought of being in the same isolated and confined space for six to eight months sounds, rightly so, like an extreme punishment. It is no wonder that science fiction is full of examples of ways to shorten the journey (warp drive, hyperspace) or awareness of it (cryogen sleep). And if there is no way to shorten the journey, who wouldn't want to pop into the holodeck occasionally for a little mini-vacation to the streets of Paris or a sandy beach?

Although interaction with virtual worlds and games can happen using high definition 2D or 3D displays, the term "virtual reality" is typically reserved for the concept of completely replacing awareness of one's actual surroundings with a three-dimensional virtual world, complete with an interface that mimics realistic, first-person interaction with the virtual environment. The most promising near-term technology for doing so is head mounted, allowing for nearly full field-of-view coverage and head tracking to update the view based on naturalistic head movements, thus achieving a full 360° view.

The draw of VR extends beyond that of simply providing a more immersive viewing environment for media and games. The hope is that VR headsets can produce more than just a viewing experience, but a sense of actually physically being somewhere you are not. This has huge potential benefit for sensory stimulation countermeasures – the ability to feel as if one has entered a completely different world is hypothesized to be of central importance for the restorative properties of natural environments, and this also opens up the possibility of information foraging countermeasures that fully engage all levels of visual and multisensory processing hierarchies.

This critical aspect of successful VR is called "presence." In a recent presentation, Michael Abrash of Valve, the makers of the Steam game platform, outlined what they have found to be key factors for creating presence (media.steampowered.com/apps/abrashblog/Abrash%20Dev%20Days%202014.pdf; see also blogs.valvesoftware.com/abrash). He distinguishes immersiveness, which is being surrounded by a virtual world, from presence – a feeling as if one is *in* a virtual world. A similar distinction has been made by other researchers (Barfield, Zeltzer, Sheridan, & Slater, 1995; Byström, 1999) who have suggested that immersion can be considered a quantifiable aspect of display technology, whereas presence is a subjective state. Presence occurs when the virtual world is convincing enough that it triggers non-conscious responses, such as autonomic arousal when standing on the edge of a cliff, or automatic reactions such as ducking to avoid an overhead obstacle. In the words of Mr. Abrash, the key to presence is convincing the "lizard brain" that the virtual environment is real, and has real consequences. Surprisingly, realistic rendering is not a strict requirement for presence – crude graphics can induce a convincing sense of presence, and excellent graphics, if implemented on a system with an insufficient refresh rate, for example, can feel fake.

More information can be found in Dr. Abrash's slides, but here we highlight the factors that Valve identified as minimal characteristics for a headset to reliably achieve presence. It should be noted that these parameters are presented from his recommendations without any additional references or research to support his claims. Importantly, these same parameters also govern the induction of motion sickness, such that creating a headset with these minimum specifications would, for the most part, induce presence and eliminate instances of motion sickness.

Table 4.2. There are several critical factors for experiencing "presence." Minimal parameters required for "presence" are in bold.

FACTOR	DESCRIPTION	PARAMETERS
Wide Field of View	Visual immersion sufficient for peripheral visual cues, which are required for motion, balance, and situational awareness	Presence starts at around ***80 degrees***; improves significantly to 110 degrees (widest tested)

High Resolution	Greater pixel density required, as wide field of view magnifies pixel size	***1080p*** seems enough for presence; 1440p or 2160p would be ideal
Low Pixel Persistence	Length of time pixels remain lit; longer persistence results in pixel smearing and blur (due to faster motion of eyes relative to head-mounted display);	***<3 ms*** for presence on 1K x 1K, 110-degree display; shorter persistence required at higher pixel densities
High Refresh Rate	Rate at which frames refresh; wide field of view and low persistence requires faster refresh rate to avoid image flicker	>60 Hz (refresh rate of a standard television) is insufficient; ***≥95 Hz*** is ideal for presence
Display Illumination	Simultaneous or scanning illumination of all pixels; eye motion causes compression/stretching artifacts	***Global display*** (illuminating all pixels simultaneously) works best; rolling/scanning display with eye tracking (eye-tracking is difficult with low-latency) posited to work
Optics	Optical magnification of image	Headset volume limits to 1 or 2 lenses, whereas ***multiple lenses/focal lengths*** *are required* to adequately account for optical distortion
Optical Calibration	Characterization of lenses and correction of (inappropriately) rendered images	*See: Optics*
(Head) Tracking	Support of positional (x, y, z) translation and (angular) orientation, such that perceptual system responds to head movement	Positional: ***1mm*** accuracy Orientational: ***0.25 degree*** accuracy (over 1.5 meter space)
Low Latency	Time from when head motion occurs to time the last photon is emitted due to that motion	***20–25 ms*** ideal; good prediction algorithms very helpful

They found that a wide field of view (FOV) is critical – at least 80°, but more is better. 1080p resolution (per eye) is enough, but 1440 or 2160p would be better. Low pixel persistence, e.g. the length of time that a pixel remains lit after being turned off, is critical for VR, as high persistence interacts with the vestibulo-ocular reflex (VOR) to produce smearing. They suggest that a persistence of 3ms or less is needed for an approximately 1000x1000 110° FOV. A refresh rate of 60Hz appears too low, while a 95Hz refresh rate eliminates flicker, and it is possible that something in between may be acceptable. Given the current reliability, accuracy and speed of eyetracking, they suggest that a “global” display is the best approach, in which all pixels of the display are rendered at all times (rather than only where a person is looking), but that this may improve over time. However, within a head-mounted display, there is only room for 1 or 2 lenses per eye, which cannot reproduce the correct optics under all circumstances, and requires highly accurate optical calibration of renderings that take into account the graphic and lens system. Head tracking must be rock solid, with a precision of 1mm for translations and 0.25° for rotations, over an area of at least 2 cubic meters, and the response latency, from motion-detection to the last photon of a view update, needs to be on the order of 20ms. Abrash suggests that a system meeting all of these characteristics could be commercially available within a few years, and that it will be based on PC technology (not gaming consoles or handheld devices).

A study of VR technology by Lin, Duh, Parker, Abi-Rached, and Furness (2002) corroborates the importance of FOV. They found that while presence was higher for large FOV (asymptoting beyond 140°), simulator sickness also increased with higher FOV. Hopefully this difficulty can be overcome by improving head tracking, refresh rate and response time.

4.2.6.1 Head-Mounted Virtual Reality Systems. Despite several previous waves of VR development since the late 1980's that have heralded the widespread production and adoption of VR technology, it has only been in the past few years that there has existed the kind of affordable, readily available platforms for VR development that are needed to spur a wide base of developers to push VR technology and applications forward (see *Appendix, Table A4*).

Oculus Rift, a VR headset and open source platform for the development of VR technology and applications, has been at the center of this resurgent interest in VR. The OR DK2 uses on OLED display with a resolution of 960x1080 in each eye and a total horizontal FOV of 100°, and can run on a laptop or desktop PC with DVI-D or HDMI graphics output. The next version of the OR headset (Crystal Cove) is looking to deliver 1080p resolution with a latency of between 20 to 30ms, low persistence, and head tracking via a mounted camera. One drawback of the current version of the OR headset is that the navigation interface only allows for tilt/pan and up/down.

Sony is also working on an LCD-based VR headset, called Project Morpheus, which also has 960x1080 resolution in each eye, with a 90° FOV and 40 ms latency. Movement is tracked with PlayStation Move controllers and the head is tracked using the PlayStation Camera. It is integrated with 3D surround audio. Several other groups are also making headset VR devices.

Some work has been done on a potential future VR technology called virtual retina display, in which an image would be formed directly on the retina at the back of the eye, rather than in a focal plane in front of the eye. Such a technology could be small and lightweight, with a large FOV (>120°) and very high resolution. It would allow for a true stereo 3D display with depth modulation, and would bypass many of the eye's optical and retinal defects. This technology is still quite undeveloped. Brother Industries debuted a prototype virtual retina display in 2010 (www.brother.com/en/news/2010/airscouter/index.htm), but there is no news of work in progress on newer versions.

In addition to the engineering issues that need to be addressed to achieve a VR headset with acceptable presence, there are a number of other aspects of VR that will require extensive additional development. On the device side, the creation of a multimodal sensory VR experience will require improvements in 3D sound, including the generation of 3D sound models and delivery of 3D sound that reflects location and material character of objects (e.g. reverb for large spaces). Work on body tracking and haptics (e.g. virtual touch, *see below*) will be important for improving presence, and will also contribute to research on better input devices for interaction with the environment. On the software side, new rules will need to be developed by game companies for how a person can move around an environment to prevent motion sickness, and for how multiple players might interact in a virtual space.

The potential applications of VR in a LDSM environment include not only gaming and the exploration of virtual worlds (e.g. Second-Life, World of Warcraft, Eve Online, MineCraft), but also other forms of exploration, relaxation and communication. Crewmembers could explore virtual worlds together, allowing for real-time social interactions "outside" of the capsule environment. Given the limitations on real-time updating imposed by the distance from Earth, platforms that allow for asynchronous updating will be required for interactions with non-crewmembers. For example, a friend or family member could record an interaction in the virtual world that could be replayed and responded to by a crewmember (e.g. a virtual "pen pal"). When combined with footage from a first-person point-of-view *recording* device (e.g. similar to Google Glass but potentially with stereo recording equipment and a wider FOV), VR headsets open up some interesting possibilities, such as the ability for a person on Earth to go for a narrated run or a bike ride that can be watched during exercise on a treadmill or stationary bike. Even without robust VR technology, existing head-mounted cameras such as those in existing augmented reality glasses or GoPro cameras, could be used to create a lower tech version of a similar experience. Although such videos are often too shaky for replay of the raw video signal, stabilization and reconstruction techniques, such as hyperlapse (http://research.microsoft.com/en-us/um/redmond/projects/hyperlapse) could take raw video and process it into a video signal that is stable and usable in a VR or immersive viewing situation.

4.2.6.2 Haptic Devices. Several devices exist for delivering touch experiences in research, gaming or VR environments. Biopac makes a haptic delivery system (www.biopac.com/haptic-delivery-system) that can be used to provide vibration in experimental or VR environments, and is intended to be placed on the floor or under a chair. There are also at least two products on the market that are wearable vests intended to provide haptic feedback during immersive game play. TN Games (tngames.com/products) makes a vest for use during "first person shooter" games that uses "air impact technology" to deliver tactile sensations at eight locations on the body, and requires a special driver that includes support for specific games. Kor-Fx (korfx.com/products) markets a "4DFX haptic feedback system" for use during gaming. It uses two, smaller haptic transducers placed on the upper chest to transduce game sounds into haptic sensations, making it usable for any audio input, including games, VR, or music.

The use of two transducers allows for some degree of directionality. Another product, Bassaware (www.bassaware.com), is designed for use with music, but could also be used with gaming, and uses a transducer to translate low-frequency sound into vibration on the back. Although this type of technology is in its infancy, the use of vibratory devices on the body surface is a promising potential direction for achieving more immersive virtual touch.

4.2.6.3 Interface Devices. The past few years have seen the introduction of a number of new types of interface devices, aimed at getting away from handheld buttons and enabling more naturalistic movements to be used to control virtual worlds. The Nintendo Wii control uses a built-in accelerometer and optical sensors to sense user motion. Sony Playstation Move works by utilizing a USB camera (PlayStation Eye) to detect motion of a glowing orb on the end of the remote and for headtracking. Microscoft Xbox Kinect also uses cameras, but does away with controllers. The cameras have sophisticated face- and gesture-detection software to let the users' bodies control the navigation.

Engineers from the Vienna University of Technology have developed a "Virtualizer" stationary system of a support belt and frame, allowing users to wear a VR headset and walk through 3D virtual environments while staying in place (www.ims.tuwien.ac.at/projects/virtualizer). Sensors in the system detect directional movement as the user securely walks above a low-friction surface. Omni by Virtuiz (http://www.virtuix.com) is a similar omni-directional stationary treadmill.

4.2.6.4 Video Games. Although a review of the various types of gaming platforms is beyond the scope of this review, there are several clever aspects of game design that are relevant for information foraging countermeasures. In order to keep people playing, games deliver a well-balanced stream of small rewards, interspersed with larger rewards for performing increasingly difficult tasks. A similar approach is likely to be successful in designing and describing information foraging. Of particular interest is the game concept of an "Easter egg," which is a hidden element of a game, sometimes something of high value, but other times something that is simply entertaining or whimsical. Easter eggs are highly sought, and acquire their special status as something worthwhile of finding by virtue of being secretive and difficult-to-find. Across a variety of countermeasures and aspects of daily life (VR, scheduling, food, stowage), hidden (innocuous) surprises can add an element of delight, and can have positive impacts on mood out of scale with the intrinsic value of the item.

Video game design also highlights the importance of considering exploratory countermeasures within the context of perception-action cycles. In a study on why people play video games, R. M. Ryan, Rigby, and Przybylski (2006) found that perceptions of competence and autonomy were associated with game enjoyment and changes in well-being before and after playing. In turn, ratings of competence and autonomy were related to the nature of game controls and the sense of presence or immersion experienced. This suggests that a beautifully rendered, sophisticated virtual world that cannot be explored on account of a poor interface is of limited use.

4.3 RESTORATIVE COUNTERMEASURES

Restorative countermeasures are designed to reduce stress, support emotional coping with stressors, restore cognitive resources and generally allow a crewmember to "blow off steam." Research on the restorative effects of natural environments (see *Section 2.3.4.2*) has revealed a number of factors that influence restoration. First and foremost, arousal-inducing sensory events, such as a sudden noise or an image of a snake, should be avoided. Similarly, restorative countermeasures should have a low requirement for monitoring and directed attention – a person should be able to feel safe, and at be ease. In addition to what they are *not*, some researchers claim that restorative settings evoke a state of "soft fascination," which could be thought of as a form of mild indirect (bottom-up) attention (as opposed to top-down directed attention). This is what distinguishes restorative sensory stimulation countermeasures from rest or sleep – restorative environments contain elements that occupy attention in a stimulus driven, non-threatening manner that is "easy" and, potentially, allow the mind to wander freely. An aspect of this property is that restorative countermeasures may also be more effective if they allow for an element of escape from the mundane ("being away") and create an environment large enough in scope to allow for a sense of immersion and unboundedness. Finally, restorative countermeasures should be compatible with a person's inclinations. For example, a small pier is compatible with a desire to fish, but not with a desire to get some mild exercise.

Although some restorative environments may also invite information foraging, the constructs of information foraging and restoration differ in important ways. For example, information foraging may be well served by highly arousing, novel stimuli to the extent that they evoke surprise, curiosity and subsequent understanding. However, restoration is best served by low to intermediate degrees of arousal – not overwhelming, but also mildly engaging. Information foraging is closely tied to pleasure from learning *new* things and the potential risks that entails, whereas restoration may be more closely aligned with the safety of obtaining pleasure from things we have *previously* learned to like.

The degree of immersiveness and presence of sensory stimulation (see above, *Section 4.2.6*) also likely plays a key role for restorative countermeasures. However, as will be discussed below, there remains much research to be done to understand how much immersion or presence are required for restorative countermeasures to be effective.

A number of technologies and countermeasures that were discussed in the section above can serve both information foraging and restorative needs. For example, visual displays and VR can be used for a variety of content. Passive media consumption can also be used for both information foraging purposes and for restorative purposes, and will not be mentioned in more detail.

4.3.1 Creating a Restorative Work and Living Environment. Restorative countermeasures can be implemented as design elements of a capsule environment. In this section we consider three aspects of design that can have positive or negative effects on restoration – decoration, including color variation, the physical layout of a space, and finally, a set of considerations that have come to be termed "biophilic design."

4.3.1.1 Color. The decoration and colors in a space can have a significant impact on the mood and behaviors of people in the space. Consideration of the aesthetic nature of a space is particularly important for an isolated and confined space that is to be a crew's sole living and working quarters for a long period, with no ability to leave. Anecdotally, color variation in spaceflight environments is an important issue – astronauts on Skylab, for example, expressed a desire for more color variation (Häuplik-Meusburger, 2011). On the other hand, there are also many popular notions about colors having negative effects on mood. Experimental work, including some by NASA investigators, has examined the relationship of color in an indoor work environment and worker mood and productivity, and has found that many of these popular notions are outdated and overly simplistic (Jalil, Yunas, & Said, 2012; Kwallek, Soon, Woodson, & Alexander, 2005). Moreso than specific colors, work by Kwallek and others over the past 20 years have found that contrasts between value and saturation of adjacent colors may be more important than specific colors, and that strong individual differences make it difficult to proscribe a single best environment for all people. In particular (Kwallek et al., 2005) found that individuals who were poor at screening out irrelevant information from their surroundings performed best in an office environment dominated by high value, low saturation color (e.g. pastels), whereas individuals with a greater ability to screen out background information performed better in an office dominated by high saturation, bold colors.

The most straightforward recommendation, then, is that it is important to not add color that feels arbitrary and that cannot be changed. Allowing a crew have a say in the color scheme, or using changeable or programmable color panels or recessed lighting, are two approaches that are likely to yield positive results with minimal harm. There exist a very large number of commercially available technologies for programmable color panels that can easily accommodate these needs - a comprehensive review of lighting devices is beyond the scope of this review. In general, the ability to subtly change the color tone of sections of walls or lighting, perhaps even with slow variation over time, could add variety without being obtrusive or overwhelming. Programmable LED or fiber-optic systems would be able to achieve these effects with minimal mass and volume requirements.

4.3.1.2 Physical Layout. The physical layout of a space of a space can affect its inhabitants' abilities to cope with reduced sensory stimulation and monotony. Importantly, the design of an LDSM mission must grapple with the issue of how to implement "time off" for crewmembers whom may be in need of rest and relaxation, but cannot leave the capsule environment and are surrounded by other crewmembers who will continue working. Separating work areas from non-work living areas, and designing the living spaces to include both social gathering space and private quarters, would allow crewmembers to feel a physical separation from their work environment. If space constraints did not allow for this, then a similar effect could potentially be achieved through the use of reconfigurable spaces that allow for the same space to take on a different character over time and be used for different purposes. The ability to stow or minimize work-related items during social time is likely to be an important factor for allowing a space to have restorative effects, and could potentially be combined with the use of lighting or display panels to create an effective shift. The use of netting for stowage is one way of flexibly reorganizing a space.

In the microgravity environment of the transit phase of an LDSM mission, this could even involve using the same space in different physical orientations, such that some surfaces serve work functions when the crew is oriented in one direction, but a social or relaxation function in another direction. Given the potential for disorientation of working in a space with multiple reference frames, such a utilization of weightlessness in capsule architecture should be coupled with sufficient training in weightlessness for astronauts to learn to function in different reference frames and switch between them.

During surface phases of a LDSM, such as those on Mars, many of the same considerations will be important. However, the arrangement of the space will of course need to have a more traditional vertical layout. Munoz, Fehlinger, and Kring (2013) also highlight the importance of separating personal and shared multiuse space, and make several recommendations for a Mars habitat layout, including interspersing work areas with multipurpose areas that include windows or other design elements.

4.3.1.3 Biophilic Design Principles. Based upon much of the research cited in Section 2, there is a movement within design and architecture to incorporate “biophilic” design principles into indoor spaces. Biophilic design aims to understand what factors support human well-being and functioning within a space by incorporating research on nature-health relationships in the built environment. A recent review (C. O. Ryan, Browning, Clancy, Andrews, & Kallianpurkar, 2014) identifies three general biophilic design principles: 1) nature in the space, which refers to the presence and diversity of plant life, water bodies and other elements of nature; 2) the use of natural analogues in building materials, patterns, colors and objects; and 3) nature of the space, which refers to the creation of spatial configurations that are associated with positive psychological and physiological responses.

With respect to the creation of LDSM transfer and surface habitats that support restoration, there are several specific recommendations from this developing field of architecture that are relevant. First, as was detailed in Section 2 and will be further addressed below, visual and non-visual connections with nature can reduce stress and have positive health impacts. Second, they suggest that variability in temperature and airflow in a space can improve comfort over a narrowly targeted, uniform temperature. Third, they suggest the use of visual patterns with moderate complexities and fractal iterations of 3 or more in the design of interior finishes, exposed structure elements, etc. Presumably, biomorphic forms and patterns such as simulated wood or marble would fall within this range. Fourth, they highlight research pointing to the importance of prospect (presence of a view) and mystery (anticipation of something new happening) in a physical environment. Although the implementation of prospect and mystery in a capsule environment may primarily have to rely on the use of virtual windows or VR, these considerations also have implications for the design of small spaces, such as the avoidance of opaque partitions that entirely block the view across a space.

4.3.2 Interacting with Nature.

4.3.2.1 Plant Life. An increasing number of studies have documented that interactions with natural environments can reduce stress, support the restoration of attentional capacity and even promote healing (see *Section 2.3.4.2*). Exposure to real plant life, while presenting a host of challenges for LDSM, provides astronauts with certain benefits that cannot be obtained through virtual exposure. While achieving an "immersive" greenhouse is unrealistic, given the likely habitable volume of an LDSM mission, even a small amount of space for growing plants could have significant beneficial effects. A volume of significantly less than a cubic meter would allow astronauts to benefit from interacting with several small plants - to watch them grow and change, have a sense of ownership, and potentially use herbs and greens to add variety to meals.

A number of systems for growing plants have been included in previous space station programs, including Salyut, Mir and the ISS (LADA Greenhouse; www.nasa.gov/missions/science/f_lada.html). Many crewmembers have highlighted the positive effects of seeing and working with plants in a highly technological environment, in addition to the benefits of eating fresh produce (Häuplik-Meusburger, 2011). For example, Mike Foale, a Shuttle-Mir astronaut, stated that working with plants made him less irritable.

Paragon Space Development Corporation (www.paragonsdc.com) has also done work on modular greenhouse systems for use in a microgravity or capsule environment. For example, they worked on a Mars Greenhouse Experiment Module (GEM) with JPL that included a plant growth chamber and atmospheric control system, as well as a system suitable for experiments with growing aquatic plans (Autonomous Biological System).

4.3.2.2 Virtual Nature. Given the existing research on the restorative benefits of nature videos versus non-natural videos, exposure to virtual natural environments looks to be a promising restorative countermeasure. Potential interfaces and their relevant characteristics were discussed above (see *Sections 4.2.5* and *4.2.6*), though there are a number of parameters that would need to be better evaluated to determine which methods give maximum restorative effect. While "presence" is critically important for convincing VR, it is unclear whether presence is actually necessary to achieve a restorative effect or if an acceptable level of benefit can be achieved with lower fidelity immersive simulations using large screens. For example, (Weinstein et al., 2009) found only weak correlations between the restorative effects of viewing nature slides and rated immersion. In addition, the dose-response relationship between amount of time spent experiencing a simulated restorative environment and stress reduction or attention restoration is not known, nor is there a clear picture of what parameters might modulate this relationship. For example, it is not known whether simulated environments that allow for active movement through nature, versus passive viewing, provide a greater benefit, nor is it known whether conventional natural environments are the sole types of stimuli that provide restorative effects, or if other restorative environments, such as a novel fantasy landscape, could also be generated. Future research on restorative environments will be needed to better understand the factors governing their stress-reducing and attention-restoring effects.

Exposure to non-visual aspects of nature should also be included as sensory stimulation countermeasures. Even small or momentary interventions with sounds or smells can have positive impacts, and ambient noise based on nature sounds can help offset other background noise and may have effects on creativity (C. O. Ryan et al., 2014). To the degree that it is possible, immersive, or at least multi-modal, technology should be used to provide simultaneous visual and non-visual connections with nature.

4.3.2.3 Odor Modification. Certain natural smells have positive benefits in humans (see *Section 2.3.4.2*). The range of smells experienced in capsule environments is extremely limited. The delivery of smells during the transit phase of LDSM presents a unique challenge due to the fluid shift that occurs in a body in microgravity and the need for continuous air ventilation. Although a number of ambient smell delivery systems are commercially available, it is unclear if these systems would be effective (see *Appendix, Table A5*). The Biopac scent delivery system (www.biopac.com/scent-delivery-system), which is designed for controlled scent research, uses compressed air to deliver scents from cartridges, and can be controlled using software. Commercial systems diffuse essential oils (Air Aroma; www.air-aroma.com/why-air-aroma) or scent cartridges (ScentAir; http://scentair.com.au/Scent-Delivery-Systems/Scent_Delivery_Systems.html), or vaporize solid-state "Scent Rocks" (www.jjmervin.com/scent-rocks.html). Even if these technologies were adapted for close-range use in a face mask or for direct delivery in the nostril, it is unclear if an astronaut in microgravity would receive sufficient stimulation of chemoreceptors to have a pleasant odor experience. In more substantial gravity, as would be experienced on Mars or the Moon, the addition of natural smells to virtual experiences with nature would be an effective method for adding multisensory variety.

4.3.3 Music. Music is a form of media that is especially associated with restorative function. Many people find that they are able to listen to music in the background while performing other tasks, though this ability varies widely across people and musical genre. Negative impacts on attention are generally more pronounced for music containing lyrics (Shih, Huang, & Chiang, 2012). However, background music is known to increase job satisfaction and should be considered if there are not substantial attentional detriments. There have been a number claims about potential effects of different genres of music on mood and behavior. Certain alternative/rock music has been shown to have a general negative effect, while other music has resulted in clarity and relaxation (e.g. McCraty, Barrios-Choplin, Atkinson, & Tomasino, 1998; Ragneskog, Bråne, Karlsson, & Kihlgren, 1996; Sousou, 1997; Yalch & Spangenberg, 2000). However, such effects are likely to be heavily influenced by individual genre preference.

Technology for music delivery is ubiquitous, robust, and lightweight, and therefore presents little difficulty for use in an LDSM environment. In addition to the use of personal headphones (either in-ear or over-the-ear), the availability of a system for playing music in a social setting is highly recommended. Not only does it free a person from the wires associated with headphones and reduce the possibility of hearing damage, it also serves a social function.

One new development in personal audio technology is the delivery of low frequency sound vibrations through wearable haptic devices. Such a device could be considered as a method for increasing the multisensory nature of sensory stimulation in an isolated and confined environment. As mentioned previously, BassAware (www.bassaware.com) markets a device for use with personal music players that uses a tactile transducer to transmit vibrations to the trapezius muscles on the back and is optimized for low frequencies.

4.3.4 Mindfulness Practices. Meditation and visualization have a strong tradition of use as coping mechanisms for stress and improving concentration (Grossman, Niemann, Schmidt, & Walach, 2004). Although the potential benefits of mindfulness practices in situations of sensory monotony and social isolation have not been rigorously tested, there are theoretical reasons to think that they may show some effectiveness. Different forms of meditation modulate the correlation between the intrinsically oriented default mode network (DMN) and the extrinsically oriented attention networks (Farb et al., 2007; Josipovic, Dinstein, Weber, & Heeger, 2012; Kilpatrick et al., 2011). Visualization, a form of mental imagery, is thought to rely on the activation of regions of visual processing hierarchies (Farah, 1989), in concert with several frontal regions (inferior frontal gyrus, IFG; middle frontal gyrus, MFG; superior frontal gyrus, SFG; anterior cingulate cortex, ACC), and the insula (Ganis, Thompson, & Kosslyn, 2004). The posterior cingulate cortex (PCC), a node of the DMN, also shows increased activation during visualization (Ganis et al., 2004). Both of these activities may be thought of as a form of self-generated disconnection from, and expansion beyond, the confines of one's immediate environment. Future research could explore the degree to which different types of meditation (focused awareness, nondual awareness, open monitoring), or different types of visualization (guided, receptive) are associated with activation of sensory pathways or resilience to sensory monotony.

4.3.5 Biofeedback/Neurofeedback. Similar to mindfulness practices, various forms of biofeedback have been claimed to allow an individual to consciously modify brain states to promote a variety of desired outcomes such as calm relaxation, improved focus, or resilience to stress. To date there has been no substantive research on biofeedback as a specific countermeasure for reduced sensory stimulation and monotony, making it difficult to evaluate its potential. Biofeedback devices measure a signal from the body (e.g. galvanic skin response, muscle tension, heart rate) or the brain (EEG alpha) and use it to modulate a visual display or sound. These systems claim that a person can use this sensory feedback to exert conscious control over a brain/body state that is not normally subject to conscious awareness.

There are a variety of commercially available biofeedback systems available. Galvanic skin response devices, such as *Mindfield eSense Skin Response* and *GSR2 Biofeedback Relaxation System*, are two-electrode recorders of relative skin conductance. Perspiration and sweat gland activity reflect increased sympathetic nervous system stimulation, making these devices good indicators of stress and activity. EMG biofeedback systems, like the *MyoTrac Infiniti* series, relay information about muscle tension in order to practice relaxation. Many heart rate and heart rate variability devices offer heart rate control, shown to improve blood pressure, lung function, and anxiety. For example, *Heartmath* offers a computer- (*emWave2 Personal Stress Reliever*) and mobile-interfacing (*Inner Balance*, for iOS), while *PN Pulse 3 HRV Kits* contain standalone dual sensor-displays. EEG devices are described at length in Section 3.5.1.3.

4.3.6 Artwork. Although there have been very few controlled studies, there are some results indicating that exposure to artwork in hospital settings has measurable impacts on health and well-being (see Ulrich et al., 2008). In addition to attention to color and design of the physical space, the addition of artwork and artistic photography to an ICE environment (in analog or digital format) is a simple and cost effective way to meet both information foraging and restorative needs. When compared to the use of color or simple design elements, visual artwork would have the added benefit of engaging latter stages of visual processing hierarchies (Vartanian & Goel, 2004; Vessel et al., 2012). Highly moving artworks have also been shown to engage the DMN (Vessel et al., 2012; see Section 2.3.3.2), which, as was discussed previously, has been linked to disturbances in mood.

Beyond static images of two-dimensional paintings, three-dimensional artworks, artwork that looks different when viewed from different angles, sculpture, multimedia artwork and light-based artwork (e.g. Leo Villareal; villareal.net) could add visual diversity and complexity to an ICE environment. For example, Mir cosmonauts reported enjoying interacting with a small sculptural object (Häuplik-Meusburger, 2011). Visually engaging artworks could help provide a low-tech and readily available countermeasure to the visual clutter commonly experienced in cramped capsule environments.

Studies of artwork in hospital environments have found that representational artwork depicting natural scenes are associated with greater acceptance and better outcomes (Ulrich et al., 2008), in line with other work on the restorative benefits of nature. However, taste in art is highly individual (Vessel et al., 2012), and the potential benefits of other types of artwork in non-hospital settings may be underestimated. Representational artwork depicting other subject matter (people, cityscapes, events, objects) and non-representational artwork can be engaging and highly moving, and may serve both information foraging and restorative needs by supporting curiosity, imaginative thought, wonder, soft fascination and a sense of being away. However, given the highly individual nature of reactions to art, crewmembers should be given input on any permanent artistic installations (e.g. wall paintings) and digital display technology could be used to display non-permanent artwork that could be changed by the crew.

4.3.7 Creative Pursuits. In addition to the perception of arts, the creative production of a variety of art forms (visual art, dance, music, poetry, theater) is a long-time tool for relaxation, and is emerging as an important tool for restoration and resilience building as well (Davis & Thaut, 1989; S. I. Kim, Kang, Chung, & Hong, 2012; Krout, 2001; Ritter & Low, 1996). Many materials for creating visual arts (pigment or watercolor, brushes, rolled canvas, sketchbook) are lightweight and low volume. Materials for producing sculpture are more problematic; however, the inclusion of some basic building materials (e.g. glue) could allow crewmembers to repurpose other materials. One interesting possibility is that experimentation in microgravity could lead to the emergence of new forms of artwork that are not possible on Earth.

Musical instruments, on the other hand, are oftentimes larger and heavier. While it is not practical to include a variety of musical instruments for crew use, it is likely that at least one or two crewmembers may wish to include a lightweight instrument (guitar, woodwind, etc.) as part of their personal payload, and this request should be accommodated, if possible.

A variety of creative pursuits can be explored using digital software. Computers can be used to make visual artwork, music, films, and even sculpture (with the use of 3D printing technology). The inclusion of a variety of creative software on LDSM missions is a low-cost, low-volume and low-mass way of supporting restorative function. Yet, given the amount of time that astronauts spend engaged with computers and screens, it is also important to provide opportunities for creative activities using analog materials.

4.3.8 Restorative Touch. Although work on restorative sensory experiences has focused on the visual and auditory modalities, mild tactile sensations can also be relaxing and restorative (e.g. Forsell & Åström, 2012; Light, Grewen, & Amico, 2005; Wentworth et al., 2009). Given the social nature of massage, caressing touch and embrace, the use of such countermeasures is heavily dependent on the nature of the crew selected for LDSM missions. While a specific recommendation for the use of restorative touch cannot be made at this time, the issue of whether crewmembers are open to sharing touch with other crewmembers should not be ignored in the process of crew selection and training.

4.4 ACTIVE RELEASE / THERAPEUTIC COUNTERMEASURES

Active release and therapeutic countermeasures are designed to provide for release of stress and active processing of emotional events. Although this class of countermeasures is not specific to reduced sensory stimulation and monotony, they are likely to play a key role in helping astronauts build and maintain resilience in isolated and confined environments. Active release and therapeutic countermeasures can play a role both in the treatment of stress, anxiety and negative mood, but also in prevention, by helping to diffuse the effects of stressful events before they can lead to longer term changes in mood and well-being that are more resistant to treatment.

The creation of a safe and confidential environment for letting down defenses and letting go of stress (e.g. "holding space" or creating a safe "container") is a key factor for active release and therapeutic countermeasures. Care must be taken in selection, matching, and training of LDSM crewmembers to make sure that they are sensitive to the needs of other individuals to process emotions and stress, both in their private quarters, but also in situations that may be observable by other crewmembers.

The ability of therapeutic countermeasures to promote self-examination and reframing of issues through analogy, emotional regulation and perspective taking are also key to their success.

4.4.1 Exercise and Play. Physical exercise is a key countermeasure for LDSM for a great number of potential risks that astronauts may face. Lack of sensory stimulation and isolation are among the risks that exercise can help mitigate. Not only can the general stress reduction benefits of physical exercise help crewmembers cope with an isolated environment, there is some research to suggest that some of the benefit of exercise on cognitive abilities stems from immersion in the activity (Schneider et al., 2013; Schneider et al., 2010)

As has been previously mentioned here and by other authors, the integration of exercise with sensory stimulation activities such as listening to music, watching movies, or engaging in exploration of virtual environments is likely to yield large gains in both the compliance of crewmembers with minimum exercise requirements and in the physical and mental benefits of that exercise. Research into technologies that allow for more immersive experiences engaging the full action-perception cycle should be a high priority for NASA.

If possible, exercise areas should be separated from work, sleep and food areas, in order to reduce the impact of vibration, smell and space usage (Häuplik-Meusburger, 2011). Giving astronauts flexibility in their scheduling for exercise is also strongly encouraged – not only will it increase the crew's sense of autonomy, it will also allow individual crewmembers to engage in exercise in moments when they may be most in need of restorative and releasing countermeasures.

"Play" behaviors have recently been the focus of increased attention by psychologists and cognitive neuroscientists, who are interested in understanding the developmental and evolutionary underpinnings of play, as well as its adaptive benefits for both children and adults. In addition to social interaction, play serves to help train and maintain motor skills, prepare individuals for unexpected events, practice skillsets, and tension reduction in social groups (K. L. Graham & Burghardt, 2010). Astronauts report engaging in a variety of play activities, ranging from play with objects in microgravity to "swimming", yoga, and "advanced acrobatics" (Häuplik-Meusburger, 2011). Supporting play behavior, and allowing space for play to occur, should be a component of LDSM mission planning.

4.4.2 Health and Wellness Apps. Enabling crewmembers to play an active role in maintaining and improving their own mental health and well-being will be particularly important given the isolation and communication delays that will be experienced during long duration missions. In addition to regular email communication and asynchronous video sessions with Earthbound psychologists, resilience can be supported using applications that help a person track and achieve their personal mental and physical health goals. One existing application, SuperBetter (www.superbetter.com) takes the form of a game that individuals play to identify personal challenges and take small steps toward achieving their goals. The game incorporates findings from scientific findings on how to build physical, mental, emotional, and social resilience. Another platform, the Automatic Mental Health Assistant (AMHA, www.amha.id.tue.nl), which has been studied as part of the MARS-500 experiments (Voynarovskaya, Gorbunov, Barakova, Ahn, & Rauterberg, 2010), combines the use of strategic multiplayer games, monitoring of nonverbal behavior using automated techniques (e.g. face expression, voice, body movements) and questionnaire-based self assessment.

While these applications, in their current form, may be useful for helping to monitor and improve a crewmember's mood, it is unclear whether they are suited to specifically measure or track changes related to sensory stimulation levels and countermeasures. It is likely that as future research hones the set of measurement techniques that are able provide specific information about needs sensory stimulation (see *Section 3*), this information could be incorporated into future versions of assessment and resilience-building apps.

4.4.3 Therapy and Processing Techniques. Interactions with staff psychologists have been a central part of NASA's behavioral support of astronauts on past missions. Communication delays pose a challenge to traditional talk therapy sessions in which a crewmember has regular check-ins with a ground-based flight surgeon. Alternatives will need to be explored, such as asynchronous communication between crew and flight surgeons (email, recorded videos), collection of behavioral or physiological responses (see *Section 3*), and processing techniques that can be practiced amongst the crew.

With respect to the dangers of inadequate sensory stimulation and isolation, therapy as a countermeasure can serve two general purposes. The first is to detect signs that a crewmember may be experiencing negative effects of reduced sensory stimulation, monotony, or isolation, while the second is to help a crewmember develop coping strategies to mitigate the harmful effects and prevent them from getting worse. Therapy could be focused on helping a crewmember to recognize changes in themselves or others, such as changes in perceptual sensitivity, changes in attentional capacity that are not related to fatigue, or changes in emotional responsivity and mood such as a blunted response to positive events, a lack of motivation and forward-looking thoughts, or the onset of potentially maladaptive sensation seeking behaviors. In addition, therapy could help crewmembers change behavioral patterns that may compound the problems of reduced sensory stimulation, such as an avoidance of social interaction or aversion to engaging with VR technologies. Finally, therapy could also be used to prescribe specific countermeasures such as change in work focus to something more meaningful or time off for engaging in restorative sensory activities.

In addition to traditional talk-based therapies (e.g. cognitive-behavioral therapy, psychotherapy), there are several non-standard therapies that may be particularly well suited for use during LDSM. Art therapy, in which a person uses artistic media to draw or paint, not with the purpose of creating a work of art but more with the purpose of using the process as a tool for emotional processing, can be done with only minimal instruction or oversight, and has the added benefit of being very sensorially stimulating. There do also exist more structured forms of art therapy, and methods are being developed to assess their utility (see S. I. Kim et al., 2012). Similarly, dance therapy, in which movement of the body is used to help a person work through an issue, could be performed without direct oversight on the part of ground crew and stimulates the senses (see Ritter & Low, 1996). In both of these (and similar techniques), the creative process is not about the product, but about using the medium as a form of analogy – a shift in reference frame that can allow a person to visualize or feel a solution or block that they were not previously aware of.

Group processing techniques, such as the Zegg Forum (www.zegg-forum.org/index_en.phtml) and various forms of role play or "playback" therapy, could provide a small, isolated crew with a set of tools that they may find useful for dealing with issues that come up over the course of the mission, either personal or group related. In Zegg forum, individuals are given the opportunity to "share" what they are feeling with the group in a freely associative manner, and these shares are then followed by "mirrors" during which other members of the group re-enact what they feel to be the salient aspects of the persons' message or demeanor. In role play therapy, individuals are asked to act out an interaction, often taking on a role that is different from themselves.

4.4.4 Pharmacological Agents. There is a growing voice within the medical establishment that controlled and guided use of certain psychoactive substances can have therapeutic and restorative effects (e.g. Mithoefer, Wagner, Mithoefer, Jerome, & Doblin, 2011; Ramikie et al., 2014). A review of the potential use of pharmacological agents as countermeasures for reduced sensory stimulation and isolation is beyond the scope of this review. Given the high risk for negative physical and psychological consequences, the incorporation of psychoactive substances as countermeasures would critically rely on the development of specific compounds and guidelines that maximize positive benefits while minimizing negative side effects.

4.4.5 Celebrations. Existing space crews, long-duration analog crews, and military personnel all recognize the importance of celebrating holidays and milestones. Not only do these events aid in maintaining social cohesion and allow for relaxation, but they also help mark the passage of time, counteracting the potentially "timeless" nature of an unchanging environment (Peldszus et al., 2014). Such events can be combined with other countermeasures, such as creative pursuits, music, food, dance, and sports competitions.

4.5 MAINTAINING HOMEOSTATIC MECHANISMS

It may be important to consider countermeasures that are designed to help maintain homeostatic mechanisms. The fundamental concept behind such countermeasures is the finding that perceptual processes are sensitive to the statistics of the natural environment, and while many stages of perceptual systems appear to have little or no plasticity in the adult brain, there is evidence some specific systems do.

For visual processes, there is no evidence for gross changes in early stages, and the variety present in the visual sensory environment, even in an ICE environment, is likely enough to prevent any deterioration in sensitivities. As was mentioned in the section on perceptual learning, early visual areas of the adult visual system do show some degree of local, retinotopic plasticity, but generally not show more global forms of plasticity.

There are some concerns about changes in depth perception; however, as was detailed in Section 1, there is currently no strong evidence to support such changes. If future research were to raise concerns, it is possible a device making use of a lens collimator, which is a device that allows for an image to be perceived at infinite depth, could be included as a countermeasure. VR devices, which can display images with a range of depth disparities, may also provide sufficient exposure to a range of disparities (though not accommodation distances). Finally, the ability to observe objects outside of the capsule through a window would also provide exposure to large distances (e.g. the sun, Earth, Mars, stars), though the range of potential concern is more in the five to 20 meter range.

Some aspects of the auditory system, however, do seem to require more continuous tuning (see *Section 1*), potentially because they are used for guiding speech motor movements. For example, individuals who lose hearing acuity often begin to mumble, due to a lack of veridical feedback about the sound of their own voice, and the sound of other's voices. Noise in an LDSM transit or surface habitat module may be unavoidable, but it may be important to mitigate as much as possible to prevent the potential degradation of speech control. If possible, there should be opportunities for total silence can occur, as well as normal sounds (talking, music) in the absence of high amplitude noise. This could be achieved by adding additional sound proofing to one part of the habitat, or through the use of sound-insulating and noise-canceling headphones.

Given the fact that tactile and proprioceptive systems have to adapt to changes in body weight, muscle strength and agility over the lifespan, it is perhaps not surprising that proprioception can exhibit plasticity over the timespan of days or weeks (e.g. Bassolino, Bove, Jacono, Fadiga, & Pozzo, 2012; Lissek et al., 2009; Wong, Kistemaker, Chin, & Gribble, 2012). Countermeasures such as resistive training, simulated gravity, and tasks that require speeded movements and agility could be used to help keep motor-proprioceptive loops and the vestibulo-ocular reflect (VOR) in a condition more conducive to activities in gravity. One potential solution could involve a full body suit with resistance bands extending from a "ground" surface to attach to several major points along the body, such as the knees, hips, shoulders, elbows, hands. This would place force vectors on many of the major body parts whose weight and movement are sensed through proprioception.

Systems for spatial orientation also appear to show adaptability, as evidenced by the fact that astronauts report initially being disoriented in space, but then learn to adjust (see *Section 1*). Although a number of researchers and operations specialists have recommended that a constant vertical be maintained in a space, the lack of a *gravitational* down is the more serious effect. While creating a vertical frame of reference may help with navigation and working within a space, it should not be done at the loss of potential usable work surfaces and adaptability of volume to multiple uses. It may be possible to smooth the transition between a 3D frame of reference during transit phases and a single "upright" frame by adding training periods toward the end of each transit in an "upright" orientation.

4.6 FOOD

Numerous researchers have identified the central importance that food plays in any ICE environment. For long duration missions where all food for the transit to and from the destination must be packaged before the mission begins, it is even more important to understand the psychological factors that govern food acceptance and enjoyment. While a review of the many considerations related to food and potential food-related countermeasures is beyond the scope of this review, there are a few important points to consider that are specifically related to the research on sensory stimulation that is presented in this report.

1) Given the body of research showing that repetition over certain timecourses can lead to habituation and a reduction in food preference (e.g. Hetherington, Pirie, & Nabb, 2002; Kramer, Lesher, & Meiselman, 2001), research on menu fatigue should strive to understand how the time period of food repetition on a menu relates to its perceived taste, pleasure, and acceptance (e.g. Moskowitz, 2000). This may be different for different types of foods, and influenced by food complexity and intensity (e.g. Weijzen, Zandstra, Alfieri, & de Graaf, 2008).

2) As a complement to pre-prepared meals with fixed ingredients, the creation of a set of ingredients that can be combined in novel ways by the crew will help to add novelty and flavor complexity to meals.

3) The inclusion of occasional surprises in the food rations (e.g. hidden chocolate or other favorites) is likely to have an outsized positive effect by breaking up the typical rhythm with an unexpected positive event.

4) Foods that have personal relevance to crewmembers may be more tolerated over long periods. Crewmembers should be given a voice in the inclusion of foodstuffs or spices that can be used to make meals that they might commonly make or that are heritage meals from their culture and have special meaning.

5) The look-and-feel of food are important considerations in addition to taste and smell.

6) Strive for variety in texture, crunch, etc.

7) The inclusion of fresh spices would add visual and taste surprise and variety, and be something the crew could look forward to (e.g. a harvest).

4.7 SCHEDULING COUNTERMEASURES

Further work should be done to distinguish individual differences with regard the effectiveness of “free” versus “scheduled” exposure to countermeasure activities. “Free” time provides opportunities for individuals to practice self-direction, resulting in improved executive functioning (Barker et al., 2014). A separate study reports that involvement in structured activity correlates with improvements in psychological and behavioral functioning (Barkto & Eccles, 2003). While this study seems to contradict the former, the author suggests that people select themselves into organized activities. That is to say, those given the freedom to schedule their own time have a propensity for establishing structure. Thus, it is unclear if it is more productive to schedule time for countermeasures or to select individuals who are inclined to schedule it themselves.

4.8 SUMMARY

- Sensory stimulation fulfills different needs. These needs include:
    1. Information foraging
    2. Relaxation and restoration
    3. Therapeutic release
    4. Homeostatic maintenance
- The effectiveness of a countermeasure is modulated by its degree of interactivity, meaningfulness and personal relevance.
- Diversity of countermeasures and in the timescale of their operation increases the overall likelihood of effectiveness of a countermeasure strategy.
- A host of other factors (cost, likelihood of use by crew, mass, sensory domain, active/passive, social/perceptual, high/low tech) must also be considered when evaluating countermeasures.

Information Foraging Countermeasures

- Information foraging countermeasures are designed for active exploration and learning, and deliver “aha” moments. They counteract boredom, and develop resiliency by giving purpose and agency. Engagement in meaningful work, learning and educational pursuits, media consumption, communication, windows, displays and virtual reality are salient examples of information foraging countermeasures.
- Allowing astronauts to have greater control over the nature of their scientific work increases its meaningfulness. In addition to mission critical work, it is recommended that there be tools and support available for crew-led opportunistic science that takes advantage of the transit phase of LDSM.

- “Skillshares” present one potential model for crewmembers to engage in social activities that also engage information foraging. Crewmembers could take turns leading skillshare workshops where they help other crewmembers learn new skills (technical, computer, artistic, physical, etc.).
- Media consumption would be benefitted by the use of algorithms that develop personal profiles to make recommendations and prioritize network traffic (e.g. Netflix, Pandora, or similar).
- Communication delays will necessitate an emphasis on asynchronous updating (e.g. email, text).
- The benefits of real windows outweigh the disadvantages.
- Large screen “virtual windows” should also be deployed. New and developing OLED technologies represent the best fit with NASA’s future needs.
- Virtual reality (VR) is a promising platform for both information foraging and restorative countermeasures. VR technology is a few years away from being ready for wider use, but change is happening quickly. Convincing VR that does not cause motion sickness must go beyond being immersive to achieving “presence,” which is the feeling that one is *in* a virtual world (rather than merely surrounded by it). The gaming industry has identified major features contributing to presence, including improved methods for interaction, and many of these ideas are being incorporated into new technology platforms.

Restorative Countermeasures

- Restorative countermeasures are designed to reduce stress, support emotional coping, and restore cognitive (attentional) resources. A critical component of restorative countermeasures is that a person feel safe, thus requiring minimal monitoring of the environment. However, restorative countermeasures do occupy attention, albeit in a mildly stimulus driven manner requiring little effort (“soft fascination”). Other factors hypothesized as important include “being away”, large scope, and compatibility with goals.
- Degree of immersion may play a key factor in the effectiveness of restorative countermeasures.
- Aspects of habitat design, such as decoration, color and physical layout contribute to restoration and ease of use. Reconfigurable spaces and lighting may best meet these needs while not introducing unintended annoyances. Biophilic design principles should be considered in capsule design. The habitat should include separate work and relaxation/social/private areas.
- Interactions with nature, both real (plant life) and virtual (VR or large-screen displays of natural environments), should be implemented during LDSMs. Use of a greenhouse is strongly recommended. Virtual interactions with nature should strive to be multimodal (smells, sounds) and immersive.

- Music, for many people, is restorative, though preferences are highly individual. Both personal and social music playback systems should be available. New devices for increasing the immersiveness of personal music playback should be considered.
- Opportunities for mindfulness practices (mediation), exposure to artwork, engagement in creative pursuits and restorative touch should also be provided. Most of these countermeasures have minimal equipment needs.

Active Release / Therapeutic Countermeasures

- Active release and therapeutic countermeasures are designed to provide avenues for release of tension and stress and for emotional processing. they include exercise and play, health and wellness applications, therapies (both traditional and nontraditional) , group processing techniques, pharmacological agents and celebrations.
- It is recommended that exercise be combined with information foraging and restorative countermeasures, such as media consumption or virtual nature runs. These could potentially even be given a personal touch through recording by friends or family.
- “Play” behavior serves adaptive functions and should be supported.
- Mental health and wellness support by ground-based flight surgeons can be augmented through the use of computerized applications, use of nontraditional therapies by the crew (art- or dance- therapy), and group processing techniques for working through social and personal difficulties.
- Celebration of milestones and holidays allow relaxation, maintain group cohesion and help mark the passage of time.

Maintaining Homeostatic Mechanisms

- Countermeasures should be considered for maintaining homeostatic mechanisms. This is especially important for perceptual systems that inform action planning, such as proprioception, vision for action, movement and navigation, and audition for speech.

Food

- Although not a primary focus of this review, it is clear that food plays a critical role in maintaining well-being and social cohesion. It will be important to characterize the timecourse of adaptation to different types of food to combat menu fatigue. Fresh herbs, food “surprises”, special meals, and sets of ingredients that can be combined in novel ways will also aid in keeping the crew well fed and interested in meals.

Scheduling Countermeasures

- Individuals differ in their need for structure in their schedule and in their likelihood to impose structure on free time. Excessive top-down management of free time should be avoided.

SECTION 5: INTERVIEW SUMMARY

The aims of this interview study were to 1) collect first-hand information on the potential effects long-duration spaceflight in an isolated, confined and extreme (ICE) capsule environment that are specifically related to reduced or monotonous sensory stimulation and isolation, and 2) perform an operational assessment of the feasibility of potential sensory stimulation countermeasures and measurement devices. To achieve these aims, a series of interviews were conducted with individuals possessing expertise and first-hand experience of isolation and confinement in low-Earth orbit space missions and analog environments, with an emphasis on long duration experiences.

5.1 METHODOLOGY

Seven interviews were conducted. Interviewees included three astronauts, two psychiatrists (flight surgeons), one person involved with mission planning and architecture (herein referred to as “mission planning specialist”), and one analog scientist (South Pole). One of the astronauts had flown on three shuttle missions ranging in length from six to ten days. The second astronaut had participated in a number of shuttle missions as well as a six -month mission on Mir. The third astronaut had also participated in several shuttle missions and one six-month Mir mission. One of the psychiatrists had worked with over 20 astronauts as a flight surgeon, mostly on three- to six- month ISS missions. The second had also worked with a large number of astronauts as a flight surgeon as well as during training, both on shuttle and four- to six- month ISS missions. He also had extensive experience with ground crew and analog crews. The South Pole scientist was beginning his tenth winter-over assignment at the South Pole Station.

A master set of questions was developed to reflect the breadth of topics to be covered. These were grouped into the following general categories:

- Assessments of any observed effects that may have been attributable to reduced sensory environment, monotony or isolation. This included questions on perceptual effects, cognitive effects, and effects on affect and mood.
- Experiences and reactions to measurement techniques. This included questions both about measurement techniques that the person had first-hand experience with, as well as their reactions to proposed measurement techniques.
- Experiences and reactions to countermeasures. This included questions both about countermeasures that the person had first-hand experience with, as well as their reactions to proposed countermeasures.

Based upon the characteristics and experience of each person being interviewed, a subset of questions was selected for primary focus. In each case, several additional questions specific to the background of individual were also added. These questions were assembled into an interview sheet and used as a guide. Based upon the answers received to these questions, certain questions were skipped, and follow-up questions were asked where necessary.

Notes on the interviews were taken by the questioner and also by an assistant. These notes were later combined into one set of answers to ensure that no important information had been missed. After anonymizing the notes from each interview, the notes from all interviews were combined by topic area to aid in summary.

5.2 EFFECTS OF REDUCED SENSORY STIMULATION, ISOLATION AND MONOTONY

5.2.1 Perceptual Effects. Overall, the interviewees expressed very few instances of perceptual effects, and where perceptual effects were noted, they were primarily associated with the initial adaptation period to space, rather than as a consequence of prolonged exposure to an ICE environment. One astronaut, for example, referred to "space fog" that was experienced during his first mission, and included difficulties with reading and concentration. However, these effects may have been related to an issue with his glasses, and were not present on his second mission.

5.2.1.1 Vision and Spatial Orientation. Astronauts, psychiatrists and the South Pole scientist were asked about experiences or reports of difficulties with visual sensitivity, maintaining visual focus, or ability to interpret the spatial orientation of their environment. No difficulties with visual sensitivity were noted by anyone. Changes in maintaining visual focus or in spatial orientation were generally transient, and related to adaptation to microgravity. One psychiatrist, however, suggested that changes in sensitivity are not often asked about specifically.

Visual clutter was noted as an issue by both astronauts who had worked on Mir. The mission planning specialist noted that rolling shelves, a Random Access Framework, and RFID tags are being considered as ways of increasing habitat organization.

Opinions on the importance of maintaining a vertical orientation were mixed. One of the astronauts reported that he generally maintained a consistent orientation, but did experiment with trying to trick his sense of vertical. Another astronaut reported that she adapted very well to changes in orientation throughout different rooms, not even noticing that one room was at a 90° with respect to another. The mission planning specialist noted that he would be in favor of designing transit habitats to take advantage of all surfaces and orientations, dependent on the wishes of astronauts. One astronaut suggested that having a single convention is good, as it will enforce uniformity amongst the crew in how they interact with different spaces. Overall, it seems that while the interviewees echoed conventional views on the importance of a consistent vertical, they also expressed an ability of astronauts to adapt, as long as efforts were made to prevent confusion.

***5.2.1.2 Audition*.** Although no changes in auditory sensitivity or function were noted by any of the interviewees, the presence of high levels of ambient noise (55-60 dB) was noted by a number of people. An astronaut that had been on shuttle missions noted that this noise was one of the major stress factors for him, and that wearing noise-cancelling headsets was a less-than optimal solution. The mission planning specialist mentioned the possibility of using a sound generator with organic-sounding noise patterns to help mask the machine and ventilation noise.

***5.2.1.3 Olfaction*.** Questions about changes in odor perception received very little response, with one of the psychiatrists noting that this was difficult to quantify, and that the shift in fluids to the face results in "puffy face" that interferes with the sense of smell. The South Pole scientist suggested that his sense of smell did undergo changes, and noted that there is a lack of "outside smells" that is very noticeable upon arrival in a more temperate climate. The mission planning specialist noted that while masking bad odors is often considered, the introduction of new odors is less discussed.

***5.2.1.4 Taste*.** Although food was not a major focus of these interviews, there were some noted changes in taste, particularly by one of the psychiatrists, who echoed the notion that astronauts often find the food bland and ask for more intense and spicy foods. One of the astronauts did note that congestion from fluid shift affected her taste.

***5.2.1.5 Touch and Proprioception*.** On the whole, no changes in tactile or proprioceptive sensation were noted by any of the astronauts nor by the South Pole visitor. One of the psychiatrists did relate that not using the feet or legs for locomotion requires significant adaptation. The mission planning specialist did note that people in ICE environments are touching metal and plastic all day, and that they are considering how to add diversity materials.

5.2.2 Cognitive Effects. Overall, very few cognitive effects were reported that could be specifically attributed to reduced sensory stimulation, isolation or monotony.

***5.2.2.1 Attention and Awareness*.** Interviewees were asked about lapses of attention or awareness. During the initial adaptation period, both the psychiatrists and astronauts noted experiences of space fog, including a lack of concentration, inability to multitask, and generally not feeling cognitively sharp. However, these effects subsided after the initial adaptation period, and did not appear to be due to monotony or reduced sensory stimulation. One of the astronauts did report instances of missing designated start times, which he attributed to the sparseness of work, leading him to lapse into daydreaming. A second astronaut noted experience with seeing lapses of attention in other individuals that were attributable to a lack of sleep. One of the psychiatrists did note, though, that their neurocognitive battery may not be sensitive enough to pick up on more subtle and transient changes in attention. The South Pole scientist noted no difficulties in attention, which he attributes to his good sleeping habits.

5.2.2.2 Hallucinations. There were no direct reports of hallucinations by any of the interviewees. However, one of the psychiatrists did suggest that such instances may have occurred and been underreported due to worries that reporting such instances would negatively affect future flight selection. He also suggested, though, that these instances may have been related to higher levels of use of Ambien than is currently in practice.

5.2.2.3 Memory. One of the astronauts did report problems with short-term memory that began about halfway through her 6-month mission She found that she had to start writing things down, whereas that had never been the case previously. Further questioning suggested that these effects were unrelated to workload, happened with other crewmembers as well, and improved very quickly upon being back on ground. There was some suggestion that the effects may have been potentially related to being in an ICE environment (and not, say, some type of poisoning or CO_2 issue).

5.2.2.4 Sleep. Although sleep was not a focus of the interviews, and our interviewees did not offer any evidence of problems with sleep, several of them did note the importance of maintaining a regular sleep schedule, and mentioned that they had witnessed other individuals for whom a lack of sleep led to decrements in performance and mood. Interestingly, one of the psychiatrists suggested that a lack of sensory stimulation, particularly from gravity, may actually contribute to better sleep, and a need for less sleep.

5.2.3 Effects on Affect and Mood. In agreement with the background literature, there was consensus among the interviewees that the most salient effects of working in an ICE environment for long durations are on affect and mood. However, problems were quite rare on either shuttle or ISS missions. One of the psychiatrists noted variability in these effects: some astronauts report no problems and feel like they could stay longer, whereas for others, more than several months in space is too much, even in the absence of any specific crises.

5.2.3.1 Confinement. Astronauts were highly variable in their reports of situations that made them especially aware of their confinement. One astronaut did not note any situations that made him more aware of being in a confined space on Mir. A second astronaut noted one instance, in which her inability to get access to certain media (a book) made her aware of her confinement. On the other hand, a third astronaut on shuttle missions found that the lack of ability to look out the windows when waking up at night due to closed shades made him very aware of the confinement on a regular basis. The psychiatrists did note that they had worked with astronauts who had experienced claustrophobia.

***5.2.3.2 Boredom*.** When asked about boredom, the interviewees expressed highly variable experiences. Feelings of boredom were intimately related to workload, with low workload and monotony being the bigger risk. For two of the astronauts, as well as the South Pole scientist, boredom was never a problem, given their very busy schedules. There was always something for them to do. For one early Mir astronaut, boredom was an extremely salient, and difficult, aspect of his mission. It was the number one problem he noted, and it seems to have significantly colored his experience. Critically, this boredom was related to the fact that he did not have enough to do, and didn't feel as if he could engage in leisure activities while his fellow Russian crewmembers were working. He noted that the Russian crewmembers had a high workload, and did not experience boredom. He also mentioned that this boredom did not seem to necessarily increase in the second half of the mission, but was more related to specific events and technical malfunctions. One of the other astronauts, while not experiencing a sense of boredom, did express that there were times when she wished there was more meaningful work for her to do.

***5.2.3.3 Depressed Mood and Anxiety*.** In general, there were no first hand-reports of generalized dysphoria, anhedonia or anxiety. However, there were a number of more specific mentions of mood changes, as well as a general recognition of the strong potential for such effects on LDSMs. One of the astronauts did express anxiety related to situations where he felt helpless to complete certain tasks, and was worried that it would affect the quality of collected samples and data. He also relayed a story of another member of the crew who experienced a death in their family while in orbit and went into self-isolation for a few days. One of the other astronauts stressed that potential candidates need to know themselves and their susceptibility, and understand how to keep themselves engaged to stave off changes in mood. Changes in the mission schedule, particularly an unexpected extension of the duration, were highlighted as events that might have large negative impact on mood. While the South Pole scientist reported no personal issues with mood, he has witnessed problems in a number of other personnel, particularly toward the end of the long dark period, including dysphoria and anxiety. He noted that these cases often involved communication with home and awareness of events in the outside world (e.g. family).

In addition to mentioning anecdotal reports of depression in the early days of the Russian program (Salyut and Mir), both of the psychiatrists reported having specific experiences with dysphoria of crew that increased in frequency in the second half of the mission. These instances have typically been directed at specific targets, such as an unhappiness with ground communication, scheduling, delayed returns, and a lack of autonomy. It is unclear whether or not these instances could have been resolved by fixing these issues, or were instead a redirection of a more non-specific changes in mood. Again, the general consensus was that as long as astronauts have enough meaningful work, they will be happy.

***5.2.3.4 Other Emotional Changes*.** One of the psychiatrists noted that early missions at ISS with only 3 crewmembers (1 American, 2 Russian) had high rates of reported loneliness that have lessened with bigger crews. There was also mention of experiences with rage in a ground crew, and reports of rage in early Mir crews as a result of poor environment and bad communication. Both psychiatrists also relayed numerous instances of frustration that were attributed to poorly worked out procedures, a lack of autonomy, broken equipment, failed experiments, and interpersonal differences (conflicts or miscommunications).

***5.2.3.5 Motivation and Curiosity*.** In general, there were no reports of a loss of motivation or curiosity by any of the interviewees. One of the psychiatrists did mention that some astronauts express a feeling of being "done" near the end of a mission when they are ready to be back on Earth.

***5.2.3.6 Ruminations*.** A number of interviewees were asked about the nature and frequency of internal mind-wanderings and musings while in ICE environments for long durations. In general, no differences were noted in the content of self-generated thought when compared to normal life, though one of the astronauts did note a much higher frequency of internally-directed thoughts on account of feeling bored. One psychiatrist did note that astronauts do get worried about their performance and can ruminate about it sometimes, but that these are typically more related to workload and self-judgment than to isolation.

***5.2.3.7 Asthenia*.** When asked about the existence of asthenia in space, one of the psychiatrists said that yes, he does consider asthenia to be a real phenomenon, and in fact thinks that it may actually be the same thing as what NASA identifies as the 3rd quarter phenomenon. Early Russian crews were much more isolated and confined, with little stimulation, and were working very hard. However, reports of 3rd quarter phenomenon are now much less common.

5.3 MEASUREMENT

A series of questions were asked about various forms of measurement that could be used to monitor sensory stimulation, perception, cognition and mood. Direct conversations with flight surgeons were reported as being the most useful, and one of the psychiatrists stressed the importance of nonverbal cues. Given the difficulty with looking at facial cues because of fluid shifts, the quality, content, and frequency of interactions with the ground crew and fellow astronauts provide very useful information. However, it was pointed out that this really depends on the establishment of a good relationship between a crewmember and flight surgeons before a mission begins, so that the ground crew is familiar with crew personalities and can detect salient changes. The lack of real-time communication during long-duration missions raised serious concerns over how this critical aspect of crew assessment will be addressed.

One potential solution mentioned by one of the psychiatrists was the development of a standardized set of questions that astronauts would record video answers to on a regular basis, such as how they are feeling, how their week has been, and whether they have any concerns. Flight surgeons could monitor these videos for signs of changes in mood and well-being. It is unclear, though, whether a measure like this could yield information specific to sensory stimulation needs.

When considering other forms of measurement, such as the use of questionnaires or devices, the overarching sentiment was that any measure would need to have a demonstrated usefulness, for both the ground crew and for the astronauts themselves. If a tool has a demonstrated use and produces data in a format that astronauts can interpret and use to understand their health and wellness better, then they will adopt it and comply. Obtuse measures that do not yield data that can be used by the crew (e.g. are analyzed only by ground crew with no feedback) are much less likely to be tolerated. Given the number of tests and measurements that astronauts face on a day-to-day basis, it will be extremely important to find a set of measures that takes the minimal amount of time and has proven effectiveness. Tolerance for large test batteries at regular intervals, with little meaningful output, is low.

5.3.1 Computer-based Tasks. Computer-based applications, including both questionnaires and task-based measures, are already being used extensively to measure cognitive skills and mood. The interviews we conducted did not go into much depth on the nature and extent of the tasks that individuals had experience with, and in general the interviewees had very little to say about such tasks. One astronaut expressed a general reluctance to engage in computer-based tasks, while another expressed some interest in specific training simulations. Again, it was stressed that tasks with demonstrated usefulness would be accepted.

5.3.2 Physiological Measurement. The potential use of physiological measures was similarly greeted with a lukewarm response, indicating that such measures would be tolerated as long as they were not too intrusive, and had demonstrated usefulness. Wristband devices, which are already in heavy use, were generally seen as acceptable, whereas one individual expressed that the use of electrodes on the face or fingers would likely be too invasive, particularly if skin abrasion is required. However, There is a risk of a lack of compliance even with wristband devices, if the data is not locally available, interpretable, and seen as useful.

5.3.3 Video for Eyetracking and Facial Expression Recognition. Similar to other measurement devices, reactions to measures based on video-camera technology stressed a balance between invasiveness and usefulness. Remote mounted cameras at workstations or in work areas were generally seen as acceptable, but cameras attached to the head, or in private spaces (bedrooms, bathrooms) were not. There was a general feeling that cameras in some areas would be tolerated, to the degree that they provided necessary data and privacy was respected. One of the psychiatrists pointed out that while such devices would normally be unnecessary for LEO spaceflight where there exists an established rapport and direct communication, they may be more helpful for LDSM.

5.3.4 EEG and fNIRS. Very few of the interviewees were familiar with either EEG or fNIRS technology. In general, the same concerns were raised – any device must be easy to set up and use, not intrusive to wear, and have a demonstrated value. Showing their usefulness in an analog environment would be a necessary precursor to their adoption in spaceflight. One of the psychiatrists mentioned that he would love to see EEG used to assess sleep quality. The mission planning specialist stressed that as long as power consumption is low, these technologies could be considered, and that if EEG proves useful, they could work on isolating it from electrical noise. He did express a potential concern of interference from RFID devices.

5.4 COUNTERMEASURES

5.4.1 Habitat and Environment. Interviewees were asked about countermeasures that relate to habitat design, decoration, and layout.

5.4.1.1 Spatial Layout and Design. Several salient points were made regarding the spatial layout and design of LDSM transit and surface habitats. In addition to the importance of maintaining organization and discipline in how space is used, the presence of personal space was repeatedly emphasized. One astronaut strongly suggested that there needs to be a separation of work and "home" quarters that is a dedicated social space for games, relaxation and eating, where the crew can congregate. Personalized touches such as pictures of home or natural scenery were mentioned, and the mission design specialist mentioned that they are exploring ways to make spaces personalizable. Design elements need to be flexible and tested beforehand, or else they risk being negative contributors to the space. The South Pole scientist, for example, expressed strong negative views to large (static) color panels on the wall ("they are awful.")

5.4.1.2 Windows. When asked about windows, there was strong support for their importance, and almost universal support for their presence on any LDSM craft, despite the lack of Earth views. All three astronauts and the South Pole scientist expressed how important seeing outside is, even if the only view is of stars, and both psychiatrists highlighted how much of a psychological boost they are. The installation of the cupola on the ISS, for instance, helped tremendously with mood. Windows can be used for science as well (cameras, telescopes), and will be very useful upon arrival at the mission destination. One psychiatrist did raise the potential concern that watching the Earth recede and having nothing to look at could be a psychological negative. However, most of the other interviewees countered this suggestion, saying that even looking at distant stars is better than having no window.

The size of a potential window is important. Windows that are too small (like those on Mir) are not very helpful. The mission planning specialist suggested at least a half meter across, and mentioned that while windows are heavy, the are actually better radiation protection than aluminum, and are not a thermal concern.

***5.4.1.3 Large Visual Displays*.** Large visual displays (screens or projectors) to be used for showing images, artworks, or movies, were endorsed by most of the individuals interviewed. Although the concept of a "virtual window" was not as familiar to some, others strongly endorsed the idea of showing changing pictures and scenery. The mission planning specialist said that the use of ultralight deployable monitors that can potentially cover an entire wall, or projections onto existing surfaces, are being very actively considered, but that large monitors, which are heavier, present more of an issue.

***5.4.1.4 Non-Visual Connections to Nature*.** In addition to support for showing images on large screens, two of the interviewees brought up the notion of non-visual connections to nature. For example, the combination of natural sounds, smells, and imagery was very exciting to the South Pole scientist, who expressed that these immersive natural experiences were perhaps what he missed most (including smells of fruit, rain, the ocean, bread, etc.). However, the mission planner pointed that not everyone will like the same odors, especially across nationalities. They have been considering the use of natural materials, such as cedar, to impart natural smells and texture into the capsule environment.

***5.4.1.5 Plants / Greenhouse*.** The importance of having real plants on board a LDSM was very highly endorsed by all but one interviewee. And while that one astronaut did not find plants to be personally meaningful, he recognized their likely interest by others. Several individuals stressed that the ability to watch plants change and grow, and to play a part in their growth, was very valuable and provided a strong connection to something bigger than their immediate surroundings. One psychiatrist mentioned that he gets repeated requests for real plants on board ISS, and that it is a big morale boost. At the

South Pole Station, there is a small greenhouse that is used for food and relaxation, and is used by a proportion of the staff, though a relatively low proportion. Herb growth could be used to augment food as well as provide visual and olfactory stimulation. The mission planning specialist suggested that at least 2 m^2, as much as 6 m^2 could be devoted to a greenhouse. The potential concerns are bacteria growth, containment, and the potential development of allergic reactions or immune responses.

5.4.2 Work, Learning, Hobbies

***5.4.2.1 Meaningful Work and Opportunistic Science*.** Perhaps the major takeaway from most of the interviews was the importance of engaging a crew in a substantial amount of meaningful work every day. Every individual expressed that this was the number one factor that affected their mood and their level of boredom. Too little work led to irritation and boredom.

Given the fact that an LDSM may have long periods where there is not work related to the final target, we asked a number of questions related to the concept of "opportunistic science" – science that was more related specifically to the transit trajectory between Earth and another object in the solar system. In general, the reaction to such opportunities for doing science during the transit phase received support, with the caveat that the direct, meaningful involvement of the crew in the substantive aspects of the science was critical. In other words, opportunistic science that is being done at the behest of an Earth-based PI with little to no input on the part of the crew does *not* meet the need for meaningful work – crewmembers want to have a role in experimental design, interpretation of data and real-time decision making of how to proceed. One of the astronauts stated that the inclusion of instruments on board the transit craft that would allow for crew-led science during the transit phase would be very stimulating and engaging. Other individuals expressed a strong interest in engaging in projects that involved working with electronics, building scientific instrumentation and equipment, etc. These are individuals who want to be actively engaged in science and exploration, and are generally less interested in just "passing the time." Interestingly, the mission planning specialist stated that while opportunistic science is being considered, no connection had been made between this and crew well-being or mission success, as the primary mindset on the planning side is to get the crew "from point A to point B." The primary challenge for the inclusion of any equipment for performing opportunistic, crew-led science would be the addition of mass.

***5.4.2.2 Balancing Work and Leisure Time*.** When asked about how to best balance work and leisure time, the general consensus was that there needed to be plenty of work to do, at least enough for a full work week. This is partly because astronauts in space feel an obligation and duty to work, given the expense and effort that has been put into getting them into space. Second, several individuals stressed the need for flexibility in scheduling leisure time, as people need to be able to structure their leisure time in ways that suit them best. Some individuals need a strict schedule with a lot of structure, whereas others can fill their own time with projects and hobbies. Lastly, the issue was raised that a major difficulty for LDSM will be to figure out how to give an astronaut "time off" from work that feels separate and restorative, despite the fact that they are physically unable to leave the capsule where other people will still be working and there is nothing new to experience.

5.4.2.3 Learning and Skillshare. Interviewees were asked their thoughts on providing opportunities to learn different things while on an LDSM. In particular, they were asked about the potential benefit and participation in skillshares, where crewmembers would take turns leading sessions to share skills and learn hobbies in a relaxed setting (e.g. a musical skill, a technical or computer skill, or a physical skill like acrobatics), potentially even new skills that were acquired in the training period before an LDSM mission. One of the astronauts stressed his desire to focus on mission critical science and suggested that extraneous hobbies did not feel like a good use of the time. Another astronaut and the South Pole scientist were both supportive of the suggestion. At the South Pole, crewmembers already teach classes on various hobbies and interests (such as astronomy), and these classes are strongly valued. One astronaut liked that such activities would be tailored, personal, and social, adding to team cohesion and shared experience, and one of the psychiatrists mentioned that the crew would know each other quite well by that time, so this could be a potentially successful countermeasure. He suggested that something like this could be tested in Antarctica. One issue that was raised was that very little time would be available before the mission for individuals to learn new skills or hobbies, given the rigorous training schedule.

5.4.3 Communication and Media Consumption

5.4.3.1 Media. It is clear that a large amount of digital media can be included on any LDSM. The important considerations are that 1) individual tastes may differ widely, and that 2) any "interactive" media needs to be designed for asynchronous updating. Responses regarding interest in music were quite individual, but the general consensus was that it should be available. When asked about the potential for using computational techniques (AI, machine learning, etc.) to develop personalized media profiles (such as Netflix, Pandora, Art.sy), most individuals expressed strong enthusiasm, stating that this approach made a lot of sense. Privacy concerns were raised, and would have to be dealt with.

5.4.3.2 Communication. Communication with friends, family and ground crew was universally recognized as extremely important. For many individuals, the ability to have asynchronous communication (texts, emails) was very important, and is likely to be a central aspect of LDSM communication. However, there was also support for the development of technology for splicing pre-recorded material with live-stream material to create a viewing experience that feels more interactive and personal, even in the face of long communication delays. One astronaut did note that she found video communication to be stressful, do to feeling like she was “on a stage.”

5.4.3.3 Virtual Reality and Gaming. Given the amount of attention and effort within the LDSM planning community on the importance of virtual reality platforms for future spaceflight, it was surprising to hear the rather lukewarm response to VR technology on the part of the interviewees. The most likely reason for this discrepancy is age – a number of the interviewees were of a generation where computer interaction was less a part of early life, and who have little or no experience with recent trends in immersive technologies. One of the psychiatrists echoed this concern, stating that many potential astronauts were “not gaming people” and that they would seek personal interactions over virtual worlds. However, the other psychiatrist suggested that if they were proven effective and were not “goofy” that they would be accepted and valuable, and one of the astronauts acknowledged that given the limitations on communication, virtual substitutes for interactive exercise or exploration could be useful. In general, it was our sense that the thoughts of the interviewees may not reflect those of a younger generation of potential astronauts who may be more excited about the potentials offered by VR with strong “presence.” The mission planning specialist mentioned that he currently prefers the use of larger displays over headset VR, but that this may change as VR headset technology improves. In a follow-up question, the mission planning specialist expressed support for a dedicated VR area of a transit vehicle, though he did not think that a VR area with artificial gravity would be feasible given the size requirements.

5.4.4 Active Release and Therapies. Interviewees were asked about countermeasures to help release stress or have therapeutic effects.

5.4.4.1 Exercise. Exercise will clearly continue to be a central aspect of an astronaut’s life in space. Despite recognizing its importance for maintaining muscle condition, two of the astronauts expressed that they were dissatisfied with the forms of exercise they encountered on their missions. One expressed a dislike of the stationary equipment and mentioned that temperature was a big issue, while the other complained that current NASA exercise regimes are focused on individuals, with no social component. This person suggested that consideration be given to group exercise activities, such as a microgravity equivalent of volleyball, that are social and competitive and promotes teamwork. The South Pole scientist also recognized the necessity of exercise, stating that he does weights occasionally while down there, which he never does while at home. He also mentioned group sports. In a follow-up question, the mission planning specialist mentioned that resistive bands/tubing may not be sufficient to address the challenges of muscle atrophy and bone loss, and may also suffer from longevity issues in long duration radiation environments.

When asked about the use of media during exercise, several people mentioned that very boring exercises were really only tolerable when listening to music or watching movies or TV, and that highly engaging programs were the most preferred. It was suggested that continuity of characters and plots that really pull a person into a show are the key factors that are sought. This suggestion also fit with the general reaction to combinations of exercise with gaming or VR – people were generally supportive, and liked the idea of using these technologies to make exercise more interesting, engaging, and if possible, more social as well. The mission planning specialist mentioned that exercise equipment is often very heavy, so they would prioritize lightweight technologies that add multisensory stimulation.

5.4.4.2 Creative Pursuits. Despite the very real limits on the amount of weight that is likely to be allotted for personal gear, most of the interviewees agreed that supporting creative pursuits is a good idea. Musical creativity has been very successful both at the South Pole (there are many instruments) and on the ISS. Artistic pursuits have been less tested, though the South Pole station does have an arts and crafts room that is used quite often (mostly by non-scientific staff). It was again mentioned that activities like this are highly individual and can't be programmed, that they are better when they can be done in a way that encourages social interaction, rather than as a way in which individuals isolate themselves, and that some individuals may not be as likely to engage in non-mission related activities that they don't see as meaningful.

5.4.4.3 Mindfulness. The interviewees who were asked did not have much experience with mindfulness techniques. One psychiatrist stated that he is a big proponent and teaches people to use them regularly to help them with sleep or stress management. The other stated that they do not use meditation currently, and don't train crew in these techniques. Both thought it would be worthwhile to give LDSM crews professional training in these techniques.

5.4.4.4 Therapy and Processing Techniques. Although both psychiatrists have experience with and regularly use certain forms of therapy (e.g. Cognitive-Behavioral Therapy), neither had much experience with nontraditional group processing techniques or art/dance therapy. It was stated that such techniques would need to have proven usefulness in order to not be viewed as "soft." The South Pole scientist stated that he thought that training in group processing techniques would be extremely helpful for them, as there have been a number of issues that could have benefitted from a forum for processing and de-escalation.

5.4.5 Food. Almost no interview time was dedicated to questions about food, given the number of other groups working on these issues. However, a number of interviewees mentioned that 1) people get bored eating the same foods and need variety, 2) tastes change and people seek out spicier food, and 3) mealtimes are important social events that help with team cohesion, and scheduling should allow for the crew to eat together.

5.4.6 Miscellaneous. Below is a collection of miscellaneous thoughts that came out of the interviews on a variety of topics.

- Pharmacology: a psychiatrist expressed his belief that the medicines that would be needed to deal with mental health issues in space don't really exist yet, but he hopes they will.
- Personality profiles: a psychiatrist suggested that personnel should be selected that are flexible and well-balanced
- Biofeedback: the South Pole scientist stated that some biomedical equipment is available but not used very often
- Active release: one of the astronauts relayed a story about the importance on long Navy missions of chances for crew to blow off steam. For one day halfway through the mission, an officer encouraged people to yell and scream at each other to "get it out of their system."

5.5 SUMMARY AND OVERARCHING ISSUES

5.5.1 Studying the Potential Effects of Reduced Sensory Stimulation on LDSMs. Several issues were highlighted during the interviews relating to future research on reduced sensory stimulation and its effects. First, it was noted that with current 6 month missions, there generally are very few effects of sensory deprivation seen, and that longer missions at ISS or at analog facilities will be needed. Second, it was also noted that any effects of reduced sensory stimulation need to be studied after the end of an initial adaptation period.

However, several interviewees mentioned that they had real concerns about the potential risk of reduced sensory stimulation for LDSMs, given the lack of direct communication, tight quarters, and lack of views of the Earth. Therefore, despite the difficulties, the interviewees expressed support for research on the potential effects of reduced sensory stimulation and countermeasure development.

5.5.2 Deployment of Sensory Stimulation Countermeasures. Despite a the relative paucity of evidence directly linking reduced sensory stimulation in ICE environments to negative effects, the individuals interviewed were broadly supportive of the deployment of sensory stimulation countermeasures. For example, despite his heavy involvement in his science on a day-to-day basis, the South Pole scientist expressed very enthusiastic support for increased sensory stimulation countermeasures. Given his many years of experience in an analog situation, this suggests that sensory stimulation countermeasures and attention to opportunities for meaningful work and opportunistic science are likely to be much more important than may be indicated by experience with short duration and ISS missions. Mission planners also appear to be vey supportive of sensory stimulation augmentation, provided that they do not incur a large cost in terms of mass & volume. Balancing this tradeoff between efficacy and mass/volume will be of central importance.

5.5.3 Summary. Overall, interviewees were aware of very few effects attributable to sensory stimulation. Isolated instances of changes in perception and cognitive abilities were noted, but without clear links to sensory stimulation levels. In agreement with the literature, effects on mood (boredom and subsequent dysphoria and anxiety) appear to be the biggest potential area for problems. This is especially true for the personality types that are typically chosen for space missions.

Measurement tools must be proven to be effective, results should be available and interpretable to the astronauts (not just ground crew), and their use must be justified as a worthwhile tradeoff given their potential for negative impact on personnel function and privacy. However, astronauts appear generally open to the adoption of novel, effective measurement techniques.

Meaningful work emerged as perhaps the most important aspect to consider in countermeasure development for reduced sensory stimulation. Although the existing literature does not make a link between reduced sensory stimulation and meaningful work as a countermeasure, these interviews strongly support the existence of such a link. For highly functioning, curious, science-minded individuals, having work on which they are engaged, have decision making capacity, and is scientifically and personally fulfilling is the number one way for them to feel stimulated and happy.

Opportunities for self-led "opportunistic science" have an important role to play in augmenting other mission-critical work. For example, the circumstances of one of the astronaut's Mir mission (equipment failure, language/cultural barriers) led to a very poor overall experience. The presence of *alternatives* for doing other science, if a critical piece of equipment fails, could allow a person in such a situation to redirect their energy into other meaningful projects. This has implications not just for scheduling, but also for equipment and instrumentation.

Several habitat and environmental countermeasures, such as windows, plants, large screens and dedicated space for non-work activities received very strong support. The response to VR and gaming countermeasures, on the other hand, was rather lukewarm. However, this may reflect the properties of the sample, and responses may be different in a sample of future astronauts and with improvements in technology. Multimodal experiences emerged as an important consideration.

There were a number of highly divergent opinions expressed about some of the countermeasures (e.g. virtual reality, creative pursuits) and the relative importance of structured vs. unstructured time and work vs. free time. This suggests that it is important for NASA to decide on whether LDSMs should be viewed as “mostly work” or as incorporating “work-life balance,” and that personnel selection and mission training needs to reflect this. Planning a “balanced” mission but then selecting and training individuals to prioritize work above all else (or vice versa) is likely to result in problems.

Most of the nontraditional proposals, such as meditation, creative pursuits, skillshares, etc. received some support from the interviewees. However, such countermeasures were endorsed to the degree that they would promote social cohesion rather than individualistic behaviors, that they could be deployed in a flexible manner, and that they don’t have large mass/volume requirements.

SECTION 6: RECOMMENDATIONS

Based upon the literature review and operational assessment performed, the following recommendations were developed to aid NASA BHP in the development of a research program for sensory stimulation augmentation. The first set of recommendations relate to higher-level aspects of creating a research program related to sensory stimulation augmentation and to specific countermeasures. Following these are some additional recommendations for specific areas of experimentation. Where possible, specific comments related to potential research in NASA's analog laboratory (e.g. the Human Exploration Research Analog, HERA) are noted.

6.1 RECOMMENDATIONS FOR RESEARCH PARADIGMS AND COUNTERMEASURES

6.1.1 Create a Taxonomy of Sensory Stimulation Functions. Sensory stimulation meets multiple needs, and chronic stress from a lack of sensory stimulation can arise in different ways when these needs are not met. NASA should support research into the creation and validation of a taxonomy of sensory stimulation function, and countermeasure development should proceed along a trajectory that targets these separable needs in a principled manner. On the basis of this literature search we suggest this initial taxonomy:

- information foraging
- restoration/relaxation
- active release
- homeostatic maintenance

Future research would benefit from models of each of these needs, as they have different causes, timecourses, and associated countermeasures. For example, a model of information foraging would be needed to derive a dose/response curve for the received benefit of exposure to an information foraging countermeasure.

A critical component of this taxonomy will be to identify markers that distinguish an information foraging need state versus a restoration need state. This will allow several related issues to be addressed. First, there is a need to understand the relative role of attention depletion versus stress in the negative effects of boredom (lack of information foraging) and positive effects of restoration. Second, it is unclear whether the ability of different countermeasures to reduce stress is specific to only one need state, or is more general. For example, can a restorative countermeasure reduce stress that is induced by threat to life, or only stress that is induced by fatigue and attentional depletion?

6.1.2 Develop an Individual Differences Approach. Understanding individual differences in a) the ability to tolerate sensory monotony and social isolation and b) what types of stimuli people find engaging, is critical for LDSM crew selection and countermeasure development.

A categorical approach to individual differences would involve the identification of a set number of personality profiles relevant for sensory stimulation, coupled with recommendations for an appropriate mixture of personalities in an LDSM crew and development of countermeasure regimes specific to these profiles. Measuring boredom susceptibility and personality traits would form a core part of this approach.

A second, "data driven" approach would make use of machine learning algorithms to develop highly individualized recommendations for countermeasure deployment. This could incorporate existing technologies for media curation (Netflix, Pandora, Art.sy) but could also go beyond this to non-media based countermeasures and scheduling. Not only would this approach help maximize the effectiveness of media-based countermeasures by increasing personalization, it would also help optimize the use of bandwidth of deep-space networks for information that is most likely to have the desired effects.

The development of personalized profiles will also aid in the optimization of individualized schedules and timelines of habituation for different crewmembers. Some individuals may find leisure time to be extremely necessary, whereas others may find it to be stressful. Some individuals may tire of the same food or activity more quickly than others. Providing targeted flexibility in timelines and choices of activities will be aided by the creation of personalized profiles.

6.1.3 Incorporate Validated Measures of Affect and Mood. There is a strong need to improve the measurement of validated constructs of affect and mood in spaceflight contexts. Not enough data is being collected on this (given its importance), and where it is, the measures being used have questionable validity. Current testing batteries focus on cognitive function, and future LDSM batteries will need to incorporate more probes of affective function. Our recommendation is to develop *stimulus-evoked affective response* measures to augment and eventually replace questionnaire based methods, as they are likely to have higher construct validity and sensitivity.

6.1.4 Link Meaningful Work and Opportunistic Science to Sensory Stimulation. There needs to be a shift in how meaningful work and opportunistic science are viewed. Engaging in meaningful work is a primary way in which crewmembers obtain diversity and richness of sensory and cognitive stimulation and develop resilience to monotony. Opportunistic science (particularly during the transit phase) that is not related to the primary mission serves a critical function. This work is not just about the potential benefit to Earth-bound investigators, but also plays a key role in behavioral health by keeping crewmembers meaningfully engaged in work where they play an active role, particularly if it is of personal interest and they have the knowledge and tools necessary to make decisions about the direction of the research.

6.1.5 Support Contact with Nature. The need for contact with nature is real and pressing. An "all of the above" approach should be taken to providing such contact: large-screen virtual windows, real windows, VR interaction (e.g. "active" exploration) with simulated natural environments, and the presence of real plants. The principles of "biophilic architecture" that pertain to physical layout, materials, visual and non-visual contact with nature should be applied in transit and surface habitat design to both work and non-work spaces. This may include non-stationarity of the physical environment (e.g. temperature , airflow). NASA should seek out and support research on the degree of immersiveness or presence of simulated natural environments that is necessary to achieve beneficial restorative effects.

6.1.6 Introduce Novelty and Variety using Unscheduled Surprises. The importance of novelty and variety, across many different sensory modalities, and in both work and leisure, is well documented. Positive surprises, particularly when obtained as bonuses for some degree of effort, can have outsized benefits on affect and well-being. Such "Easter eggs" could be introduced over the course of the mission in payload, communications and scheduling.

6.1.7 Develop "Presence" in Virtual Reality. Existing virtual reality technology is not yet able to reliably meet the needs of sensory stimulation. However, it is not that far off, and investments in development of immersive VR technologies that increase "presence" are likely to have payoffs in the very near-term (several years). Societal changes in the acceptance of VR technology and gaming platforms is also happening swiftly and will increase its importance as a platform for countermeasures.

6.1.8 Improve Technology for Objective Measures of Internal States. Although devices for measuring objective correlates of perceptual, cognitive and affective states (i.e. EEG, fNIRS, facial expression recognition, psychophysiology and eyetracking) are likely to play an increasing role in LDSM, many of these technologies still have relatively low signal-to-noise ratios and are unproven for real-time use in an operational context. However, investments in the development of these measurement techniques are likely to have near-term payoffs (3-10 years), allowing for more objective measurements of internal states that do not rely on questionnaires or human observation.

6.1.9 Engage in Celebrations. The celebration of holidays, special events and milestones support group cohesion and help mark the passage of time. Even solitary individuals look forward to such events. This may be especially important in an LDSM context where it may be difficult for one individual to relax on their own while their counterparts continue to work. Group celebrations signal that it is okay for everyone to put down their work and relax. These celebrations could also involve the incorporation of other countermeasures, such as music, creative pursuits, food and active tension release.

6.2 POTENTIAL EXPERIMENTS

In addition to the larger experimental goals expressed above, here are a few additional research questions that should be explored.

6.2.1 Effects of Reduced Sensory Stimulation on Anhedonia and Anxiety. Since the end of sensory deprivation experiments in humans, there has been little work exploring the effects of reduced sensory stimulation and monotony on mood. For ethical reasons, it is *not* recommended that NASA BHP take on a sensory deprivation research program.. However, it is possible to find other ways of exploring the effects of reduced sensory stimulation. A number of approaches are already in use, such as the study of analog environments and simulations. Experimental studies of people working in Antarctic stations, on whaling ships, in naval submarines, and in factories may be able to yield relevant data. It may also be possible to learn important information from individuals who have lost forms of sensation as result of traumatic injury (e.g. eye, ear, or nerve damage). Experimental studies that manipulate high versus low sensory environments for short periods in non-clinical civilian populations may also be of some use in specific situations. Finally, the development of an animal model may also be a fruitful approach, such as the development of transgenic mice strains whose sensory input can be selectively downregulated.

Within these potential model systems, the important research questions would be 1) does reduced sensory stimulation lead to anhedonia (loss of pleasure and engagement with normally pleasurable activities or stimuli) independent of social isolation, and 2) if so, whether the anhedonia is specific for the reduced stimulus domain, or is a more general loss of pleasure for all potential rewards. The answers to these questions will help determine the degree to which sensory stimulation augmentation must be specific to the reduced sensory or cognitive domain, or whether a more general augmentation approach is sufficient to make up for the lack of one domain.

Similarly it will also be important to understand whether reduced sensory stimulation has specific effects on resilience to stress and on anxiety. Using a stress-inducing paradigm (e.g. cold or heat or workload), anxiety and resilience could be compared in high versus low sensory environments.

Several aspects of this research agenda could be explored in HERA or other analogs. First, responses on measures of anhedonia such as questionnaire measures and task-based measures (e.g. measures of “liking” and “wanting” and reward-based learning) could be measured over the course of study participants’ time in HERA and compared to non-isolated individuals with similar levels of workload. Of particular interest may be to track both "physical" and "social" anhedonia to determine if they are dissociable in such simulations.

6.2.2 Time Constants of Perceptual and Hedonic Adaptation. Perceptual sensitivity and hedonic (liking) reactions change over repeated presentation of the same stimulus. The nature (decreases, increases, U-shaped functions) and timecourse of these changes varies by sense and stimulus type, and likely also differs by individual. For example, some people can listen to the same musical playlist all day for several days but can't stand to eat the same meal twice, whereas other individuals may be the opposite.

Planning for LDSM missions would greatly benefit from a characterization of the nature of change over repeated engagement with a variety of stimuli (foods, music, images, games, activities). An important goal of this research program would be to characterize the optimal time delay between repetition of the same item for minimizing perceptual and hedonic adaptation. Assuming that this optimal delay may vary across individuals, it would also be important to characterize what factors predict optimal time delays.

LDSM analogs could be used to compare the timecourse of change of hedonic responses to visual, auditory and food stimuli for individuals who are in an isolated environment versus a control group who are not.

6.2.3 Measuring Directed Attention Using Bistable-Perception. In Section 2, evidence was presented linking the restorative effects of natural environments with the availability of resources for maintaining directed attention. Based upon the cited literature, we recommend the development of a bistable-perception task as a potential measure of changes in directed attention. Three potential candidates could include 1) Necker-cube reversals, 2) motion "plaid" stimuli composed of two gratings moving in different directions and 3) binocular rivalry. Within an analog testing environment, such a measure could be incorporated into a regular testing regime and compared to measures of fatigue and boredom. In addition, measures of directed attention across time could be compared to the types of sensory countermeasures that analog simulation participants choose to engage in.

6.2.4 Restorative Effects of Creative Pursuits. Although there is evidence documenting the restorative effects of exposure to natural environments, it is unclear whether other types of countermeasures (that may be easier to deploy during LDSM) may also have restorative effects. Very little research has been done on whether engaging in artistic and creative pursuits that invoke "flow states" such as musical improvisation, drawing, writing or "tinkering" (e.g. with electronics or optics, etc.) may also have restorative effects on stress levels and attention. Within an analog testing environment, measures of mood and directed attention could be compared between a group of simulation participants who have access to creative pursuits versus a separate group of simulation participants who do not have access to these items.

6.2.5 Easily Deployable Proxy Measures for Sensory Stimulation Needs. A taxonomy of sensory stimulation needs will aid future research (*see 1.1 above*). Future research should strive to identify easily deployable behavioral or physiological proxies of these needs from amongst the suite of available and in-development measurement techniques. In the context of analog simulation environments, mobile EEG, physiological measures, fNIRS or facial expression measurement could be piloted as measures of need states.

6.2.6 Additional Potential Uses of Analog Simulation Environments. As research in these areas progress, BHP will undoubtedly identify specific operational parameters related to sensory stimulation that can be further tested and honed in an analog simulation environment. Although many of the recommendations made above would benefit from testing in a more general research sample and environment before they could be meaningfully applied to the analog context, there are a number of potential uses for analog stimulation environments that have not been previously mentioned. Below, we will outline some of these potential uses.

- *Personalized Media Profiles*. Compare crews who have access to software for personalized media profiles (e.g. Netflix, Pandora or equivalent) versus crews who have access to media, but with no personalized profiles. Differences could be assessed using measures of stress, boredom, mood and overall well-being, as well as on the amount of time spent engaged with media.
- *Availability of Opportunistic Science*. Compare crews who have tools and instructions available for non-mission critical opportunistic science versus those that do not. In both cases, the crews would have all resources and instructions necessary for a set of "core mission focused" science experiments and work duties. An additional manipulation could include the failure of a component of a "core" science experiment, to observe how the ability to perform opportunistic science might affect crew well-being in the face of such a failure.
- *Availability of Simulated Nature*. Compare crews with access to VR simulations of natural environments to those with access to videos of nature versus those without access to either. Comparisons could be made on measures of directed attention, stress and overall well-being, at several points in time during a simulated mission.
- *Scheduling of Surprises*. Compare across crews that experience different schedules of novel/unexpected (positive) events, such as the discovery of gifts, food items, unexpected communications or time off. For control purposes, the overall number of surprises ("Easter eggs") could be controlled across each group, with only the timing

differing (e.g. regular timing, random timing, increased frequency over time, decrease frequency over time). Comparisons could be made on measures of stress, mood, overall well-being and coping.

- *Celebrations*. Compare across crews who have a specifically planned mid-mission celebration versus those who do not.
- *Olfactory Sensitivity.* Measure olfactory sensitivity over time in isolation. If changes are detected, give a crew access to olfactory delivery systems to test whether access to a diversity of odors can mitigate such changes.

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APPENDIX: TABLES OF COMMERCIALLY AVAILABLE MEASUREMENT AND SENSORY STIMULATION TECHNOLOGIES.

Table A1. Commercially Available EEG Devices. (*see Section 3.5.1.3*)

Device	Brand	Product	Class	# Electrodes	Ease of Use:	Notes	Cost	Link
EEG	NeuroSky	Mindwave	Consumer	1	Dry; headset	Includes apps/games to use, with device; more available for purchase	$79.99	<http://neurosky.com/products-markets/eeg-biosensors/hardware/> <http://store.neurosky.com/products/mindwave-1>
EEG	NeuroSky	Mindwave: Mobile	Consumer	1	Dry; headset	Communicates with mobile devices	$99.99	<http://store.neurosky.com/products/brainwave-starter-kit>
EEG	Emotiv	EPOC neuroheadset	Consumer	14	Dry; headset	No access to raw data; just use to manipulate on-screen environment	$299	<http://emotiv.com/store/hardware/epoc-bci/epoc-neuroheadset/>
EEG	Emotiv	EEG neuroheadset	Commercial	14	Dry; headset	Unlike the Emotiv EPOC, gives access to raw EEG data	$750	<http://emotiv.com/store/hardware/epoc-bci-eeg/developer-neuroheadset/>
EEG	InteraXon	Muse	Consumer/ Commercial	7	Dry; headset	Associated with application called "Calm"	$299	<http://www.choosemuse.com/products/muse>
EEG	Wearable Sensing	DSI-24	Commercial/ Research	24	Dry; cap	"QStates" software package assesses cognitive and physiological states	N/A	<http://www.wearablesensing.com/DSI24.php>
EEG	Wearable Sensing	DSI-7	Commercial/Research	7	Dry; cap	"QStates" software package assesses cognitive and physiological states	N/A	<http://www.wearablesensing.com/DSI7.php>
EEG	Wearable Sensing	DSI-Mini	Commercial/Research	6	Dry; cap	"QStates" software package assesses cognitive and physiological states	N/A	<http://www.wearablesensing.com/DSIMini.php>
EEG	Rhythmlink	EEG Electrodes (various)	Consumer/ Commercial/ Research	Variable	Wet (gel)	Individual EEG electrodes for sale; not complete EEG system	N/A	<http://rhythmlink.com/products?id=EEG+Electrodes>
EEG	Brain Products	actiCAP (various related products)	Research	16	Dry; cap	Complete system + amplifiers	<$8700	<http://www.brainproducts.com/productdetails.php?id=56>
EEG	Compumedics NeuroScan	Quik-Caps	Research	12-256	Wet (gel); cap	Complete system + amplifiers	N/A	<http://compumedicsneuroscan.com/quik-cap-electrode-system/>
EEG	EGI (Electrical Geodesics, Inc)	GES 400 series	Research	32-256	Wet (saline or gel); cap	Complete system + amplifiers	N/A	<http://www.egi.com/research-division/research-division-research-products/ges-400-series>
EEG	SAM Technology	MANSCAN	Research	84-152	Not specified		N/A	<http://www.manscaneeg.com>
EEG	Lexicor	Neurosearch 24 EEG recorder	Research	24	Wet (gel); cap		$285	<http://www.electro-cap.com/index.cfm/prices-additional-caps-and-supplies/lexicor-neurosearch-24/>
EEG	Cognionics, Inc	Cognionics Wireless EEG Headset	Research	Up to 64	Dry; cap		<info@cognionics.com>	<http://www.cognionics.com/index.php/products/hd-eeg-systems/64-channel-system>

Table A2. Commercially Available fNIRS. (*see Section 3.5.2.2*)

Device	Brand	Product	Spectroscopy Type	Wavelengths	# Channels	Coverage	Notes	Link
fNIRS	BIOPAC	fNIR400	Continuous wave	730nm and 850nm (can also emit 805 nm)	16 Channel (4x light, 10x detector)	Headband (forehead, other areas if shaved)	Wireless version available (model: fNIR100W)	http://www.biopac.com/Research.asp?SubCatId=198&Main=fNIR%20Optical%20Brain%20Imaging
fNIRS	fNIR Devices	fNIR Imager 1000	Continuous wave	730nm and 850nm	16 Channel (4x Light sources, 10x Detectors 2x 14-pin connectors)	Headband (forehead)		http://www.fnirdevices.com/products.htm
aNIRS ("ambulatory")	NASA	NINscan TD	Continuous wave	660nm to 910nm range (660nm and 905nm used in linked study)	1 light source, 2 photodiode detectors	Headband (forehead)	Uses on-board memory (not wireless). Monitors tissue hemodynamics and oxygenation, ECG, respiration, and motion/accelerometetry	http://www.ncbi.nlm.nih.gov/pmc/articles/PMC3170398/?report=classic http://www.dsls.usra.edu/meetings/hrp2012/pdf/4065.pdf
fNIRS	Hamamatsu	NIRO-200NX	Continuous wave	735nm, 810nm, 850nm	2 channels (each has 1 source+detector)	2 forehead sensors		http://www.hamamatsu.com/us/en/product/category/5002/5022/C10448/index.html
fNIRS	MRRA, Inc	Genie fNIRS	?? (Likely, Continuous wave)	700nm and 850nm	16 transmit optodes; 32 receiving optodes	Non-specified; "hair penetrating brush optodes"	"Hair penetrating brush optodes" don't require shaved areas of contact	http://www.mrrainc.com/products.php?product=Product-3 http://www.appliancedesign.com/articles/93635-eid-bronze-cortical-activityviewer-%20cav-genie
fNIRS	NIRX	NIRSport 88	Continuous wave	760nm and 850nm	8 illumination sources, 8 detection sensors	Headcap	Can use two systems in tandem (double the source-detection density); wireless; "active detective sensor technology" for measurements during movements	http://www.nirx.net/imagers/nirsport
fNIRS	NIRSOptix by TechEn, Inc	CW6	Continuous wave	690nm, 785nm, 808nm, 830nm, and 904nm	32 ***lasers (NOT LEDs)*** and 32 detectors	Headcap	Company seems willing to work with clients to make custom instruments	http://www.nirsoptix.com/CW6.php
fNIRS	Hitachi Medical Co	ETG-4000	Continuous wave	695nm and 830nm	16 photodetectors and 17 light emitters	Wired probe headset ("skullcap")		http://www.hitachi-medical-systems.eu/products-and-services/optical-topography/etg-4000.html

Table A3. Commercially Available Large Screen Displays. (*see Section 4.2.5.2*)

Device	Brand	Product	Class	Display Size (Diagonal)	Resolution	Dimensions (WxHxD)	Weight (Mass)	Cost	Link
TV	Samsung	S9C	OLED	54.6”	1920x1080	55.8”x30.6”x5.3”	60 lbs	~$9,000	http://www.samsung.com/us/video/tvs/KN55S9CAFXZA
TV	Samsung	F7100	LED (LED backlit LCD)	74.5”	1920x1080	66.1”x37.8”x2.2”	62.4 lbs	~$3,800	http://www.samsung.com/us/video/tvs/UN75F7100AFXZA
TV	Samsung	F7100	LED (LED backlit LCD)	64.5”	1920x1080	57.1”x33.1”x1.3”	50.8 lbs	~$3,700	http://www.samsung.com/us/video/tvs/UN65F7100AFXZA
TV	Samsung	F7100	LED (LED backlit LCD)	60”	1920x1080	53.8”x31.3”x1.2”	43.7 lbs	~$1,900	http://www.samsung.com/us/video/tvs/UN60F7100AFXZA
TV	Samsung	F7100	LED (LED backlit LCD)	54.6”	1920x1080	48.3”x27.9”x1.2”	32.8 lbs	~$1,600	http://www.samsung.com/us/video/tvs/UN55F7100AFXZA
TV	Samsung	F8000*	LED (LED backlit LCD)	Other LED TVs with similar specifications as the F7100 series. Exact specifications and prices vary. Other Series also exist.					
TV	Samsung	F6400*	LED (LED backlit LCD)						
TV	Samsung	S9V	UHD 4K (LED backlit LCD)	84.5”	3840x2160	74.9”x43.0”x2.2”	129.2 lbs	~$40,000	http://www.samsung.com/us/video/tvs/UN85S9VFXZA
TV	Samsung	HU9000 (curved)	UHD 4K (LED backlit LCD)	78”	3840x2160	69.1”x40.3”x5.7”	101.2 lbs	~$8,000	http://www.samsung.com/us/video/tvs/UN78HU9000FXZA
TV	Samsung	HU9000 (curved)	UHD 4K (LED backlit LCD)	64.5”	3840x2160	57.1”x33.4”x4.4”	59.1 lbs	~$4,300	http://www.samsung.com/us/video/tvs/UN65HU9000FXZA
TV	Samsung	9000	UHD 4K (LED backlit LCD)	64.5”	3840x2160	57.6”x33.0”x1.6”	70.8 lbs	~$7,500	http://www.samsung.com/us/video/tvs/UN65F9000AFXZA
TV	LG	55EA8800	OLED	54.6”	1920x1080	48.43”x28.15”1”	29.1 lbs	~$8,500	http://www.lg.com/us/tvs/lg-55EA8800-oled-tv
TV	LG	55EA9800 (curved)	OLED	54.6”	1920x1080	48.31”x31.44”x7.56”	37.92 lbs	~$8,000	http://www.lg.com/us/tvs/lg-55EA9800-oled-tv
TV	LG	84LM9600	UHD 4K (LED backlit LCD)	83.9”	3840x2160	75.43”x44.09”x1.57”	150.36 lbs	~$17,000	http://www.lg.com/us/tvs/lg-84LM9600-led-tv
TV	LG	84UB9800	UHD 4K (LED backlit LCD)	84”	3840x2160	79.7”x43.8”x3.4”	162.5 lbs	~$15,000	http://www.lg.com/us/tvs/lg-84UB9800-led-tv
TV	LG	79UB9800	UHD 4K (LED backlit LCD)	78.5”	3840x2160	73.8”x39.9”x3.4”	125.7 lbs	~$8,000	http://www.lg.com/us/tvs/lg-79UB9800-led-tv
TV	LG	65LA9700	UHD 4K (LED backlit LCD)	64.5”	3840x2160	57.13”x32.99”x1.61”	89.51 lbs	~$6,500	http://www.lg.com/us/tvs/lg-65LA9700-led-tv/technical-specifications
TV	LG	65LA9650	UHD 4K (LED backlit LCD)	64.5”	3840x2160	57.28”x34.69”x1.71”	62.61 lbs	~$5,000	http://www.lg.com/us/tvs/lg-65LA9650-led-tv/technical-specifications
Projector	LG	HECTO	Laser	100.3”	1920x1080p	21.5”x5.7”x16.0” (console) 88.4”x50.1”x0.47” (screen)	30.86 lbs (console) 70.5 lbs (screen)	~$8,000	http://www.lg.com/us/tvs/lg-HECTO-laser-tv

Table A4. Commercially Available Head-Mounted Virtual Reality Systems. (*see Section 4.2.6.1*)

Device	**Brand**	**Product**	**Class**	**Display Resolution**	**Horizontal Field of View (degrees)**	**Pixels Per Inch (PPI)**	**Total Pixels per eye**	**Weight**	**Features**	**Price**	**Link**
Virtual Reality Headset	Oculus Rift	DK2	OLED	960x1080 each eye (1920x1080 split between each eye)	100	441	1,036,800	440 g (0.97 lbs)	Positional tracking	$350	http://www.oculusvr.com
Virtual Reality Headset	Sony	Project Morpheus	LCD	960x1080 each eye	90	N/A	1,036,800	N/A	N/A	N/A	No official site available
Virtual Reality Headset	Zeiss	Cinemizer	OLED	870x500 each eye	30	N/A	435,000	120 g	Built in audio	$750	http://www.zeiss.com/cinemizer-oled/en_de/product-information.html http://www.getfpv.com/zeiss-cinemizer-oled-video-goggles.html

Table A5. Commercially Available Odor Modification Devices. (*see Section 4.3.2.3*)

Device	Brand	Product	Mode	Notes	Link
Scent delivery	BIOPAC	SDS-100	Compressed air delivery; 3-6 meter delivery	Buy separate scent cartridges (over 100 scents available); manual or software controlled release (can synchronize with other – eg. physiological recording – software)	http://www.biopac.com/scent-delivery-system
Scent delivery	ScentAir	ScentWave, ScentPOP, & ScentStream	"Dry air release technology"	Up to 1500 scents (cartridges) available; adjustable delivery and intensity settings with 24-hour timer; various sizes available	http://scentair.com.au/Scent-Delivery-Systems/Scent_Delivery_Systems.html
Scent delivery	JJ Mervin	Scent-Celine (nano), Scent-Tribe, Scent-Nova, Scent Storm, Scent Master, & Scent Max Delivery Systems	Oil-based fragrance delivery		http://www.jjmervin.com/scent-delivery-systems.html
Scent delivery	JJ Mervin	Scent-Atomizer	"Scent rocks" (super essence in a solid state) are vaporized by "Scent-Atomizer"	Distributed by air-conditioning system	http://www.jjmervin.com/scent-rocks.html
Odor removal	OMI Industries	Ecosorb® Delivery Systems	Ecosorb® (chemical) is blown around environment by fans/nozzles/sprayers	Seems targeted for industrial use, but is "safe to use in even the most confined areas"	http://odormanagement.com/delivery-systems/
Scent delivery and odor removal	Air & Odor Management (AOM)	AIRQ-150, AIRQ-1200, & AIRQ-550	AirQ erases rather than masks malodors through the use of proprietary neutralizing agents that work in concert with custom-made scents; AirSolution and BioStreme are natural odor reactants and neutralizers	Programmable start/stop times; <100 scents available; Similar to Odor Management Ecosorb® system	http://aomlanka.com/scent-delivery-system.html http://aomlanka.com/odor-control-solution.html
Scent delivery and odor removal	Air Aroma	Aromax, Aroslim, & Aroscent Diffusion Systems	"Cold air diffusion"	1000s of scents (essential oils and aroma oils) available; can use "natural plant extracts proven to reduce chronic stress"; removes odors using Arotec chemical (breaks down bad odors); sleek design	http://www.air-aroma.com/why-air-aroma

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13. ABSTRACT *(Maximum 200 words)*

The dramatically reduced levels and monotonous nature of sensory stimulation experienced in isolated, confined and extreme (ICE) environments are major potential contributors to the risk of adverse behavioral conditions and psychiatric disorders during long-duration space missions (LDSM). A literature review (covering spaceflight, LDSM analogs and cognitive neuroscience literature) and operational assessment (interviews with subject-matter experts) identified potentially mission-critical effects of inadequate sensory stimulation. This review guided the creation of a general framework for how reduced levels and variety of sensory stimulation impact perception, cognition, affect and mood in ICE environments. The framework a) identifies four key biological and psychological needs that sensory stimulation addresses, and b) delineates the ways in which sensory stimulation relates to stress and resilience. Countermeasures for meeting these need states are presented and evaluated for their effectiveness, feasibility during LDSM, and likely acceptance by the crew. Constructs relevant to the measurement of sensory stimulation and its effects are identified, and a framework outlined for characterizing individual differences in sensory stimulation needs and resilience to boredom. Finally, specific recommendations for countermeasure implementation and future research are presented, with a focus on how to identify need states (e.g. "information foraging" vs. "restoration/relaxation") and deliver targeted, "dose-dependent" countermeasures.

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